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SOLID ROCKETS: SEEKING A NEW PLATEAU

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PART II

THE STATE-OF-ART IN SOLID ROCKETS DESIGNED PRIMARILY FOR SPACE MISSIONS

for
Casefile

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The state of technology for motors intended for space launch vehicles has taken great strides in the past few years. The two basic parameters which have advanced greatly are burn time and thrust level. They carry with them, of course, large physical dimensions, great weight, and high propellant loads. The advance in burn time has been from typical military rocket levels of 60 seconds to approximately 120 seconds. Thrust levels greater than one million pounds are delivered by the 120 inch Titan III solid propellant motors, thrust greater than three million pounds will be demonstrated by early 1965 in the National Large Solid Motor Feasibility Program, and levels of six to seven million pounds will be produced by the full length versions of motors in that program. In achieving this advance, test motors with diameters of 86", 96", 100", and 120" were fired under Air Force and NASA contracts in the period 1960 to 1963 (Figure 1). These programs defined the technology of nozzles, cases, and gave confidence in the status of propellant physical properties. They justified on the one hand the development of the Titan III solid motors, and on the other hand the continuation of the large solid motor effort leading to motors approximately 22 feet in diameter and 150 feet long.

Before proceeding to discuss in detail the new technologies of the class of large motors, we should mention briefly the smaller solid motors used for space launch vehicles. The all-solid four-stage Scout vehicle is probably so well known that it requires little discussion. It is giving yeoman service, and now exists with various improved or uprated motors which provide appreciably greater payload than originally planned. Another important application in the space program is the Apollo Launch Escape System. Here, three solid motors are used (Figure 2). Numerous other solid rocket motors are used in space launch vehicles, primarily for retro and oams applications. In general, these are based on older technology and do not have requirements for exceptional performance in terms of specific impulse or mass fraction. They burn for durations of a few seconds.

The discussion of new state of technology should start with some consideration of uses. The uses are generally in vehicles carrying men, and in vehicles that also contain liquid propellant stages. The best known application is probably the Titan III vehicle, under full development. Here, two 120" diameter segmented solid rockets, each delivering somewhat over one million pounds of thrust, form the booster stage for a liquid propellant core based upon the Titan II vehicle (Figure 3). Another similar application, on a smaller scale, is that of thrust-augmented Thor. Here, three solid motors provide an assist to the liquid core, with relatively large payload increase obtained by very modest investment in development effort (Figure 4).

Other missions must be spoken of in terms of potentiality. The illustrations given show that both large and relatively small payloads can be effectively delivered by vehicles containing one or more solid propellant stage (Figures 5 and 6). These highlight the inherent flexibility of the large solid motors.

The new state-of-art indicated by the title of the paper is most directly associated with great impulse and thrust, and very little associated with specific impulse or high energy propellants. Fundamentally, the situation grows from the economics of the space launch vehicles. It requires a lot of propellants, whether liquid or solid, to bring a space payload to velocity of 35,000 or 40,000 feet per second. Studies of various launch vehicle systems shows that purchase of velocity by means of high energy solid propellants is not as economically attractive as purchase of velocity by larger amounts of lower energy solid propellants. An aspect of this situation which cannot be ignored is the fact that there is competition for some launch missions between liquids and solids, and the unit cost of materials like liquid oxygen and kerosene are very low. The solid propellant space art, therefore, has not involved deeply high cost, high energy propellants.

The new state-of-art is best represented and summarized by three motors (Figure 7). The first is 120" in diameter and is under full development for the Titan III launch vehicle. Here, thrust somewhat over one million pounds will be delivered for approximately 105 seconds, and individual motor weight will be in the neighborhood of one-half million pounds. The second motor is 156" in diameter, a dimension controlled by the maximum overland transportation capability in the country. The class of motors has an ultimate capability of approximately three million pounds of thrust with motor weight near one and three-fourths million pounds. Two segment elements of this motor have been tested, producing almost one million pounds for 120 seconds. The third motor under active investigation is 260" in diameter; just over 22 feet. It is representative of a class which has a peak thrust potential near ten million pounds per motor, with 120 seconds burn time. In the existing programs, half-length motors are being made to produce over three million pounds of thrust (Figures 8 and 9). This class of motor is basically designed for one piece construction, since the main benefits of segmentation, which will be discussed, below, are not applicable.

These motors contain most of the new basic design concepts and technologies established during the recent past. One of the most interesting concepts which may be now considered state-of-art is that of segmentation. The probable virtues and deficiencies of segmentation have been argued at great length by the solid rocket profession, but it appears that the period of contention has passed. The primary virtue of segmentation is related to the ease of handle, transport and assembly (Figures 10, 11, 12). A secondary benefit derives from the fact that segmentation gives additional flexibility in the design of the grain perforation. This has resulted in widespread adoption of a circular central (Fig 12A) perforation in many motors. The prior drawback of circular perforations was the progressive thrust-time curve resulting from the increase in the burning surface as the perforation enlarged. This has been overcome by using the end surfaces of the propellant segments. A circular central perforation, with proper design of segment end burning surface can yield thrust-time curves of almost any desired shape.

The history of tests of segmented motors has been exceptionally good. During the past four years more than 15 large segmented motors have been tested containing more than 50 individual segments, without a single failure of the joint or seal. We must not ignore the other side of the segmentation coin, however. The insulation of the joint region is critical; more total insulation is required than in non-segmented motors; more seals are involved. The cases are more difficult to make and are more expensive.

The larger number propellant and surfaces means more flaps, potting, inhibiting. One of these secondary factors was probably responsible for at least one of the very few failures in the total large motor program.

The large non-segmented, monolithic motor cannot be considered a novel concept, although the dimensions and weight are impressive (Figure 13). It is generally found that length-to-diameter ratios do not exceed those established in prior years by relatively small rockets. The monolithic motors are almost unlimited in thrust and impulse potential since they are not limited by the restrictions of overland transportation. Diameter could grow well beyond 260", with the primary limitation being burning rate and physical properties of the propellant. It appears that motors as large as 30 feet in diameter could be made now, if they are wanted.

The next area of new technology is related to motor cases. The dimensions of the case parts are greater than those encountered in smaller motors, obviously: cylindrical sections can be almost 3/4" thick, and the transitions and bosses, can be almost 3" thick. A key problem in making parts of these thicknesses is the heat treating technology, and specifically the availability of heat treating facilities. No facility in the country has a capability for motor cases larger than about 12 feet in diameter. This state led to serious examination, about two years ago, of a relatively new class of steels known as maraging steels, which contain approximately 18% nickel. Maraging steels obtain their strengths through an aging process at the moderate temperature of 900°F and do not require quench or controlled furnace atmosphere. Needless to say these virtues would not be useable in the absence of good mechanical properties. A great deal of examination of the fracture toughness of the marage steels has been made with the conclusion that they are, if anything, superior in fracture toughness to the well known missile grade steels, at least in the yield strength range above 200,000 pounds per square inch (Figure 14). The principle drawback of the class of steels is the relative lack of knowledge about the details of smelting, rolling, welding, forming, inspection, etc. The marage steels were finally selected for the 156" and 260" diameter motors, and the results have, in general, been very good (Figure 15). As a family, they have demonstrated considerably greater plain strain fracture toughness than the quench and tempered steels.

Even weldments of the steels, which are less tough than parent material, show greater plain strain fracture toughness than is observed in the conventional heat treated steels at the same strength level.

A vast amount of effort has been devoted to investigating and defining the weld conditions. Tungsten inert gas welding, metal inert gas welding, submerged arc and other methods have been examined and the TIG and submerged arc methods selected for production by the three main fabricators. The 18% maraging steels are quite readily weldable and are rated by the fabricators as giving less difficulty and requiring less weld repair than other steels. The proof of the pudding is of course the eating: more than ten 156" motor segments have been made of the marage steel and hydrotested successfully. One motor 156" in diameter has been successfully fired; the cylindrical and head components of 260" diameter motor cases are now in the process of welding, with no appreciable difficulty (Figures 16, 17, 18).

The process of aging these segments to bring them to yield strength of 200,000 to 250,000 pounds per square inch has proved to be fairly straight forward. For 156" segments, existing annealing furnaces have been used with temperature of 900°F for 4 to 8 hours. The 260" motors require the construction of new aging chambers. A satisfactory method for local aging of welds has been developed by one fabricator. The unit consists basically of a portable strip furnace which is placed around the motor case at the point of the final weld (Figure 19). This method is used consistently with satisfactory results. It is also used to re-age components or welds when repairs have been necessary.

This raises an extremely interesting and valuable point concerning the marage steels. During a period of about 2½ years one major fabricator of 156" diameter marage steel cases has produced 150 tons of finished product, has used about 47 miles of weld rod and made about 3,500 test bars of various configurations. He has found it necessary to make nine repairs and re-works, and concludes that the marage steel lends itself to major re-work and repair at any stage of manufacture and testing. The opinion of this well experienced rocket case fabricator is that the marage steel is far superior to the previous missile grade steels he has worked with. The important factors that make this re-work possible are the following: 1) the steel has extreme toughness with high strength; 2) it can be welded in either the annealed or aged condition; 3) it can be locally aged; 4) it has extremely high dimensional stability resulting in minimum distortion in welding and aging; and 5) it is possible to predict with relatively high confidence, the dimensional stability during and after thermal treatment.

Some typical examples of the repairs are as follows: a 120" diameter hydro-burst vessel lost its bolted-on closure from delamination of a plate which was made from the first production heat of steel. A new closure was made, a forging was cut from the original case, the new closure was welded into the case, the weld was locally aged, and the repaired vessel passed the second hydrotest at the design strength level of 270,000 pounds per square inch.

A 156" diameter segment was found by ultrasonic inspection to contain a delamination. (Incidentally, the delamination was discovered through the use of improved ultrasonic testing method devised by the Naval Research Laboratory and Excelco Company.) The questionable area, which was 4 inches by 24 inches long and on a spherical surface, was removed and replaced with a new piece of plate. The segment was aged, finish machined, and successfully hydrotested. It formed part of a motor recently fired successfully, and has since passed another hydrotest.

A 156" diamter cylinder was completed; on final inspection subsurface cracks were found and a section of the case one foot in diameter was removed (Figure 20). A new plate was welded in, locally aged and the segment passed hydrotest.

These examples of the special properties of the marage steel are of considerable interest in relation to the possibility of reusing rocket motor cases by recovering them from flight vehicles.

It would not be proper to give the impression that no difficulties have been encountered in the use of these steels. There is a tendency for lamination to occur in the steel, possibly as a result of austenitic inclusions. This condition can result in delamination of the plate near cut or welded edges or regions. It also may result in low through-thickness strengths, especially for sections above about 1½ to 2" in thickness. Tentative inspection methods have been devised and are being used, to detect banded steel plates and a great deal of work at mills and in fabricators plants is being done to pin-point the causes and the cures.

The marage steel has been found to be well adapted to rolled ring forgings. It is also found to be readily formed by sheer spinning with requirement that greater sheet rates be used than for other rocket motor case steels. In this fabrication, reductions of 80 to 82% are possible without re-solution annealing.

In summary it might be said that the level of successes in fabrication has been surprising and gratifying; the number of failures, deficiencies and flaws have been relatively very small, and the marage steels seem to be a fine choice for large motor cases.

The next major technology advance might be classified as conceptual. It involves the nozzles. The problem is to make a rocket nozzle with a throat diameter of perhaps eight feet and an exit diameter of 20 feet or more. As stated earlier, the burning time to which these nozzles will be exposed is of the order of two minutes. What materials can be used? Before propounding an answer, a very important factor must be highlighted: thrust or specific impulse of motors of the large size is essentially unaffected by an inch or two change in nozzle throat diameter. In other words, an ablating nozzle is satisfactory (Figure 21). This is extremely fortunate, because on examining available materials for nozzles of this size, one considers refractory metals, block graphite or laminated structures of graphite and carbon cloth (Figure 22). The refractory designs are quickely put by because of the difficulty of making them and of the weight and the cost. The use of block graphite is possible and has been adopted for some 120" motors. Its use is limited, however, by the unavailability of graphite blocks larger than about five feet in diameter, except on an experimental basis. Consequently, the technology developed for very large nozzles has been based on the ablative laminated structure. A typical design uses a carbon tape entrance section, a graphite tape throat section, a carbon or graphite tape exit region, and finally a silica tape exit liner (Figure 23). The fabrication process involves winding of the tapes on metal mandrels under properly controlled pressure from rollers (Figures 24, 25). The tapes have been previously impregnated with the bonding agent, and are in a semi-cured, dry state. After completion of wrapping and machining, the components are cured at a few hundred degrees in hydroclaves or autoclaves. Final bonding together, machining, and insertion into the nozzle shell completes the fabrication (Figures 26, 27, 28).

The test record of large nozzles of this kind is not extensive to date, but the results are sufficiently conclusive to verify the concept (Figure 29). In the most recent test, with a 156" diameter motor which produced almost one million pounds of thrust, the ablation rate on the most critical part of the nozzle, the throat, was less than 0.003 of an inch per second, appreciably less than the estimates made on the basis of smaller scale tests. Thus over the approximately 120 seconds burn time, the radius of the nozzle throat changed less than one-half inch.

Conceptually, the wrapped ablative nozzle design seems satisfactory. From an engineering and quality control standpoint there is much that needs to be learned. Some test firings indicate that the angle of wrap of the various materials must be carefully controlled. Quality control relating to the rippling of the laminate material must be stringent, since the erosion rate is strongly dependent on this factor. Standards for inspection, qualification and general quality assurance must be established.

The state of thrust vector control technology for solid rocket motors has advanced greatly in an engineering sense in the past three years. The three systems which have been either developed or evaluated on large motors are liquid injection, jet tabs, and movable nozzles (Figure 30). All of these techniques were demonstrated in principle on smaller rockets as long ago as 1957 through 1959. The real accomplishments in recent years has been the proof of structures with ability to stand the longer 120 seconds burn time, rather than the typical early rocket burn time of 60 seconds, and the extension of fabrication technology to the large dimensions required for large motors. The most highly developed system is the secondary injection method (Figure 31). Thrust deflection angles of at least five degrees can be attained, and recent improvements in the injector design has resulted in excellent side specific impulses (Figure 32). Clever design for redundancy results in a highly reliable system in spite of the numerous components.

The jet tabs were recently tested on the firing of the 156" diameter motor with thrust level of almost one million pounds and duration of approximately 120 seconds (Figure 33). A second test will be made before the end of this year. The results of the firing give good confidence that the jet tabs can be developed for very large motors. This system, too, can give six degrees or more of equivalent jet deflection.

The third vector control method under investigation is that of the moving nozzle; more specifically the fully gimballed nozzle. The tests so far have involved motors 65" in diameter with throat size of 15". The basic concept is an outgrowth of previous designs but the nozzle is of the laminated ablative design described earlier. In two tests of 15" diameter throat nozzles, 60 second runs were obtained with no failure of operation or seal. Within this calendar year the nozzle will be tested on a motor 156" in diameter with throat diameter of 38", for burn time of 120 seconds. The thrust level will be almost 1½ million pounds, the motor weight 3/4 of a million pounds (Figure 34).

The art of vector control for solid rocket motors, we see, is in pretty good state. One concept is highly developed, and two other designs have been evaluated on intermediate size rockets. In discussing the performance potentialities of such systems it is well to review the requirements for very large space vehicles. Consider two vehicles, with payload to orbit capabilities of 500,000 or 125,000 pounds, and with solid propellant first stages, and liquid propellant upper stages. Without fins, the thrust vector control requirements are equivalent to four degrees jet deflection; with fins, the requirements are much less (Figure 35).

Another important new concept which has been established during the immediate past is a method for processing, casting and curing very large and heavy motors. The pressure to derive a new methodology for making very large motors, grows from the difficulty of moving them. The conclusion is that it is more desirable to move equipment and tooling to the fixed motor than it is to move the multi-million pound motors through a fixed plant. This leads to the combination cast-cure test facility (Figures 36, 37). In principle it is simple - a hole in the ground about 120 feet deep and 50 to 55 feet in diameter. The motor case is placed on a thrust jack in the pit, nozzle end upward; propellant is brought to the motor and cast into it; curing takes place in the pit without moving the motor, and ultimately, static firing takes place in the pit. A final possibility in relation to the pit is that it can be built with flood gates which allow it to be flooded so that the motor in a suitable caisson can be floated out, and placed on a barge for delivery to a launch and preparation site (Figure 38).

Two complete new facilities, based upon this concept, have been built and are now operational. Both have been provided by company funds.

The state-of-art of motor insulation is based largely on smaller rockets, with one exception. Most of the insulation for the large motors is made of loaded rubbers, the loading usually being silica or asbestos. In general, the insulation is pre-formed from rubber sheet which is bonded together and cured in a vacuum bagging operation in autoclaves. The thickness of insulation in large motors may be as great as three inches, and generally, the thickness is varied and contoured to match the predicted insulation requirements (Figure 39).

One new technology under development is that of slurry insulation. A rubber mastic compound is put on to the walls of the motor case by a hand troweling operation, followed by pneumatic tamping. A great virtue of this method is the short processing time compared to the pre-molding operation, and the possibility for lower cost. There is a question, of course, of erosion rate. Thus far, the erosion rates seem to be at least equal to those shown by the pre-molded insulation (Figure 40). Two of the 260" diameter motors to be made and tested in the next 12 months will use insulation based on this concept.

Now, having discussed the technologies to make a complete motor, we will consider the question of ignition. Two new concepts of ignition have evolved over the past few years, and one of them has been brought to a fairly advanced state of development. They are aft end ignition and hypergolic ignition. The aft end igniters used for the very large motors are generally of the pyrogen type, generally designed to burn for about ½ second.

The concept has the igniter pointing into the motor through the exit cone, with a track and cable device for allowing the igniter motor case to be removed from the exhaust stream of the main motor.

Hypergolic ignition involves the use of a reactive liquid which is brought into the motor case through the nozzle and which is sprayed on the propellant surface, usually near the forward end of the grain. A sufficient number of tests with hypergolic ignition have been made within the past three years to prove conclusively that it is a feasible and in some applications an attractive system. Either of these systems lends itself admirably to pad mounting. This means that a great degree of reliability and redundancy can be built in to an igniter system without penalizing a flight vehicle by excess weight. For a launch vehicle with a booster stage made of clusters of motors, this factor becomes important. Needless to say, in such a design it is absolutely essential that all motors be ignited, and the pad mounting set-up is an additional assurance of ignition of clusters. Another ignition concept tested extensively during the past two years to achieve high reliability for ignition of clusters is based upon the concept of cross-communication among igniters. In this scheme, each igniter motor is joined to all others by a small diameter tube which allows the combustion gases to serve the function of ignition in the event of failure of the electrical initiators. The method has worked well.

Our discussion to this point has concerned itself with state-of-art which has become fairly well established. We would now like to mention a few items which are in an earlier stage of investigation, but which give good promise of success, and which offer advantages or capabilities not now available. One important technology that appears ready to blossom is that of failure warning systems. As is well known, a manned launch vehicle has a requirement that the human payload must be saved in the event of the failure of any part of the system. In liquid propellant vehicles, failure warning and abort systems have been developed and are in use. The anologous warning systems for solid booster vehicles are obviously not nearly so highly developed. The investigation and developments over the past few years have resulted in methods for dealing with one primary failure mode; over pressurization, and more recently for dealing with burn through. It is a fortunate fact that the very large motors of the class we have been discussing are relatively immune to the effect of propellant cracks or flaws which produce over-pressurization. As an illustration, in a 260" diameter motor, a full length, full webb, depth grain crack would result in a 17% increase in burning area with concomitant pressure of 837 psi relative to a failure pressure of 870 psi (Figure 42). It appears that the motor can take the full crack without failure. A separation 20 feet long in the cylinder, however, around the entire pheriphery of the case is sufficient to reach the minimum chamber pressure. This amounts to about 1,500 additional square feet of burning area. The significance of this condition is that there is considerable time to detect the onset of a pressure rise resulting from excess burning surface and to activate escape systems. The instrumentation required for doing this is not new and would consist of existing pressure transducers and a proper electronic set-up.

The second major failure mode, case burn through, is much more difficult to deal with. This mode can be related to the previous one, because the extra burning surface which leads to pressure rise may be located at a boundary where it also can lead to temperature rise and burn through. The problem of detection of overheating seems at first insurmountable, since there could be more than 10,000 square feet of motor case surface to monitor. However, during the past two years the effort along this line seems to have produced results. A liner and insulation material containing electrically conductive layers has been developed which is satisfactory in every way with respect to compatibility with propellant and performance as insulator. A tungsten electrode is placed in the motor cavity, and since the combustion gases are good electrical conductors, a circuit as completed when the conductive layers are exposed by a burn-through (Figure 43). The method has been tested in small motors and appears to give a large and unequivocable signal when the burn-through reaches the conductive layer, allowing ample time for activation of an escape system (Figure 44). Within the next two years it is expected that this concept will be checked out on large motors and will become an accepted part of the large motor technology.

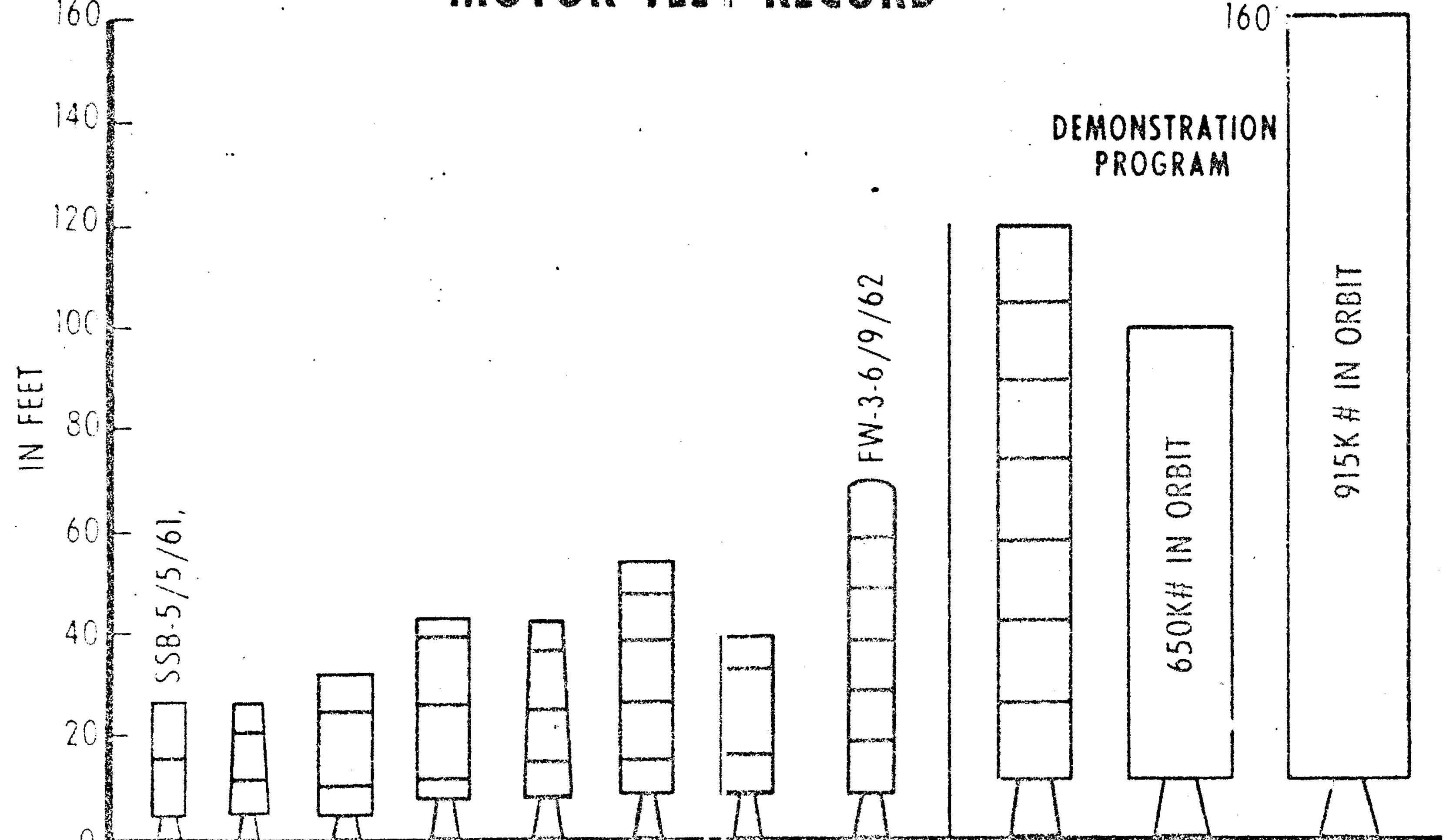
Another special concept which we may have mentioned in passing is worth discussing further now. It is the re-use of motor cases, insulation and nozzle component. The experience of the past years shows quite conclusively that the motor case segments of the segmented motors can be re-used. The 156" diameter motor tested in May is now in the stage of reprocessing for re-loading and firing. This program, in fact, was predicated upon the re-use of the motor case. Numerous other examples can be given of individual segments that have been re-used once, and one or two segments have been re-used twice. There seems to be no reason why even greater re-use cannot be obtained. The idea of case re-use is probably not new; more novel is the re-use of the insulation system. The 156" segmented motor is now being re-processed for the second firing with the same insulation system that was used in the first firing. The charred layers of insulation were removed by buffing and grinding, and the remainder is found to be adequate, with large reserve, for the second firing. An interesting side-light on this motor is that it was requalified by hydro-test after the first firing with the insulation in place. The metal shell of the nozzle will also be re-used. Although it has not yet been attempted, it is interesting to consider whether the entire nozzle of a large motor might not be re-used in a similar manner.

The question of hazard classification and safety demonstration is not usually considered to be a state-of-the-art item. There have been recent tests in this area, however, which are of sufficient interest and significance to be worth reviewing here. The question of the hazard classification of the propellants in terms of their TNT equivalents is usually dealt with by arbitrary tests in which high explosive donars are placed on motors or charges. The composite propellants now being used for very large motors are classified in this way as a class II fire hazard only with a TNT equivalence of less than 20%. Considerable concern has been expressed by range safety personnel about the hazards that might develop from the destruct or fall back of a very large solid motor. A recent test to deal with this question has been accomplished. In this test, a short segmented 120" diameter motor was mounted upon a sled, and propelled under its own power to a speed of 650 feet per second. It was released while still burning, and while it still contained more than 80,000 pounds propellant, and flew into a concrete wall seven feet thick, backed up by a few inches of armor steel. These conditions of velocity and propellant load were computed to represent the worse circumstances of drop of a motor this size. The result was gratifying, if spectacular. The various gauges monitoring the impact indicate extremely low TNT equivalent, probably under 5%. Much fragmented unburned propellant and large pieces of of motor case was recovered from the area. All evidence indicated that no detonation had occurred.

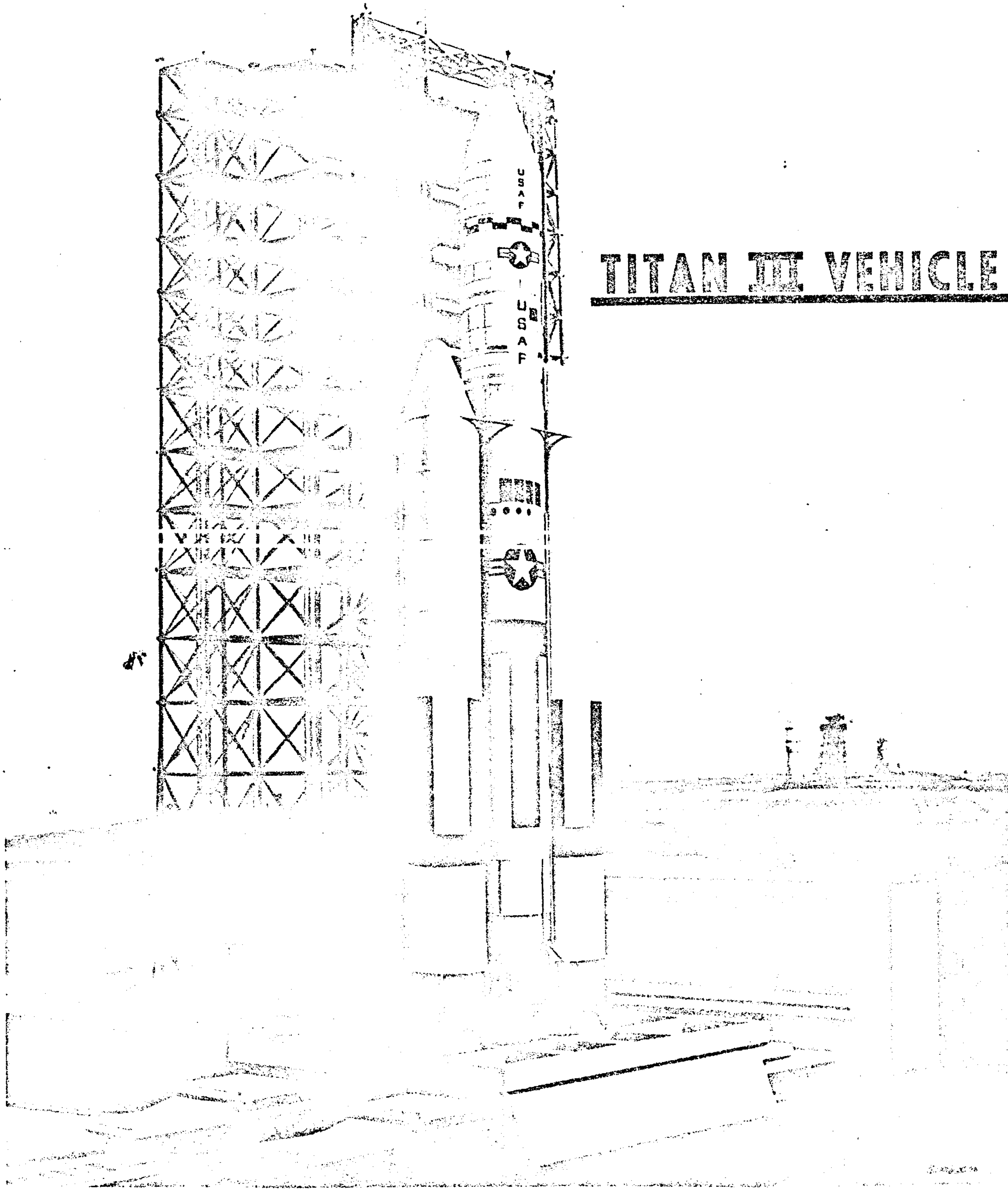
The final technology we wish to discuss concerns the cost of the new classes of solid motors. We mentioned earlier in the paper that cost effectiveness is quite important in appraising the relative merits of propulsion systems for large launch vehicles. It is a fortunate fact that the increase in size of the rocket motors has resulted in a decline in the unit cost of the completed motor. This can be easily rationalized, since it is clear that the greater amount of propellant put into a motor, the larger proportion of the low cost element is used. The illustration (Figure 46) shows that one of the early 100" diameter motors, fired in 1962, was made at a cost of $2.75 per pound, and projections of unit cost into the large motor area indicate unit cost near $1.50 per pound including thrust vector control system (Figure 47).

In this section of the paper we have concentrated mostly on the new but fairly well-established state-of-art of motors and components which are applicable to the national space effort. The items discussed in detail are almost ready for use by the total solid rocket industry. Perhaps within a short time they will provide the path to the new plateau of use we foresee by our review.

NATIONAL LARGE SOLID MOTOR PROGRAM
MOTOR TEST RECORD



DIAMETER	65"	86"	100"	100"	96"	100"	20"	100"	156"	260"	280"
WEIGHT (1000 LBS)	51	73	108	161	140	234	198	353	1.6 MILLION	4.0 MILLION	5 MILLION
THRUST (1000 LBS)	150	210	413	420	380	534	300	750	3.0 MILLION	7.0 MILLION	10 MILLION
BURN TIME (SEC)	60	70-134	46	67	77-120	88	130	41)	120	120	120



Figure

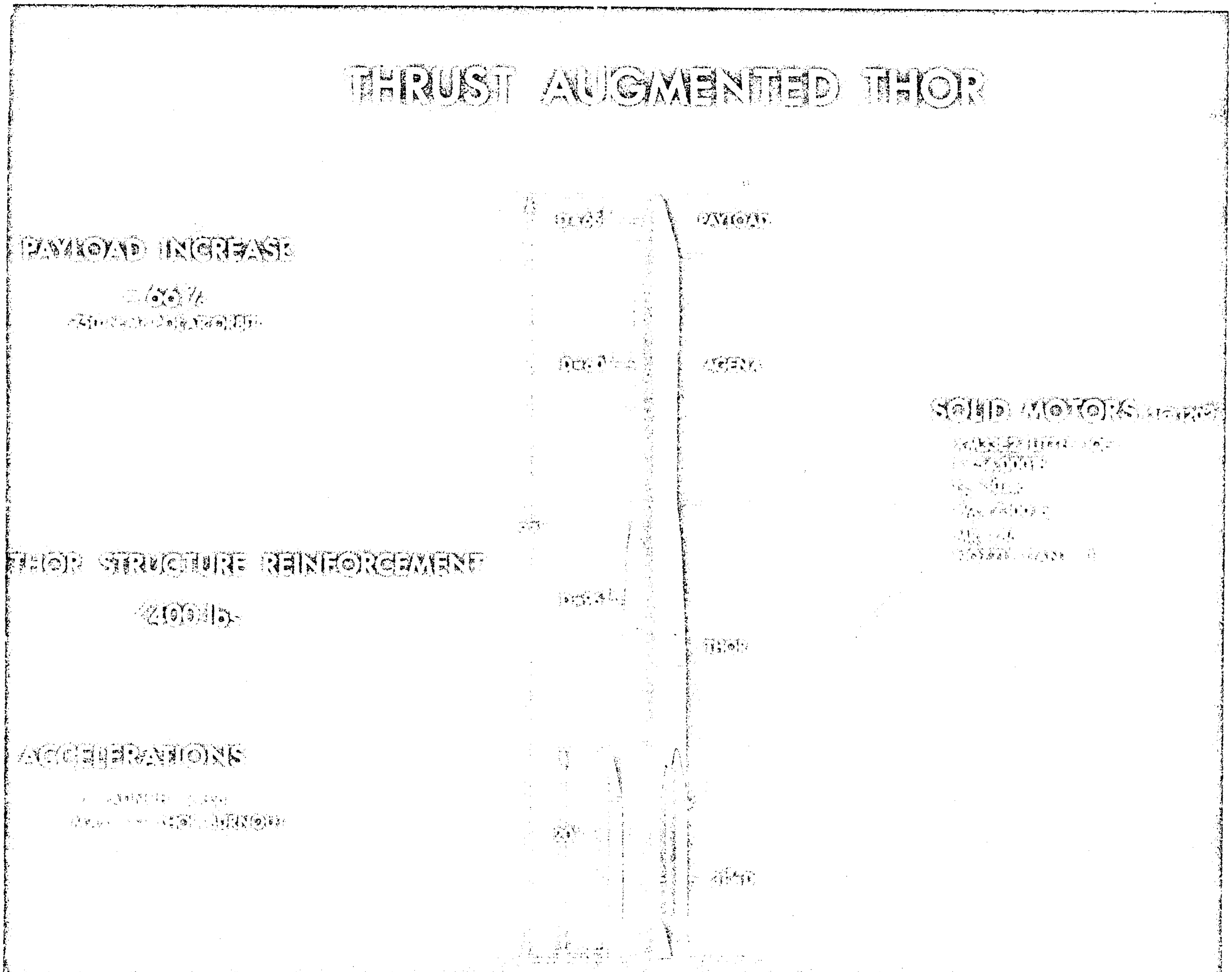

THRUST AUGMENTED THOR
PAYLOAD INCREASE
60%
THOR STRUCTURE REINFORCEMENT
400 lb
ACCELERATIONS
SOLID MOTORS
PAYLOAD
AGENA
THOR

Figure 4

SOLID BOOSTED LAUNCH VEHICLE CAPABILITIES

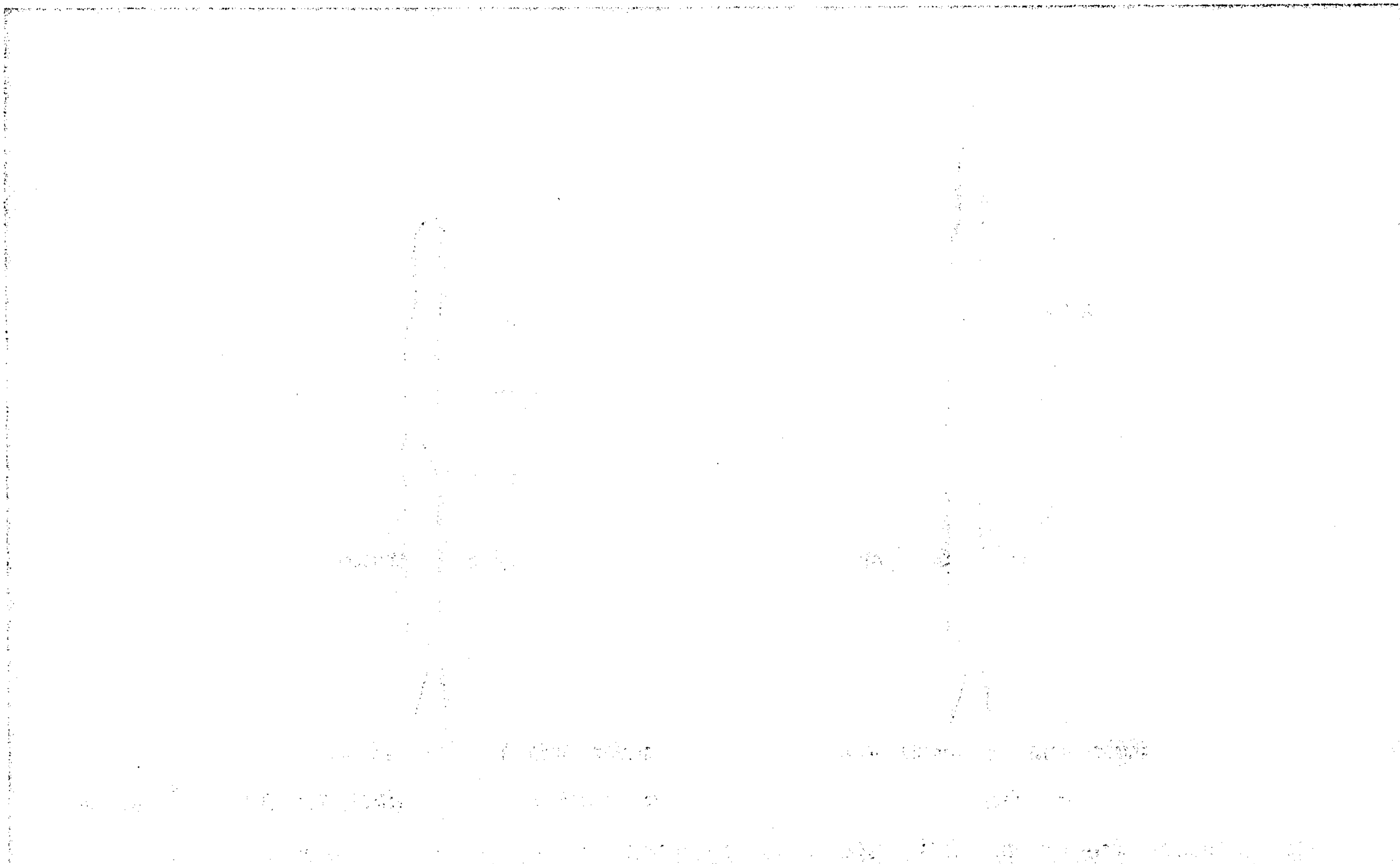


Figure 5

SOLID-BOOSTED LAUNCH VEHICLE CAPABILITIES

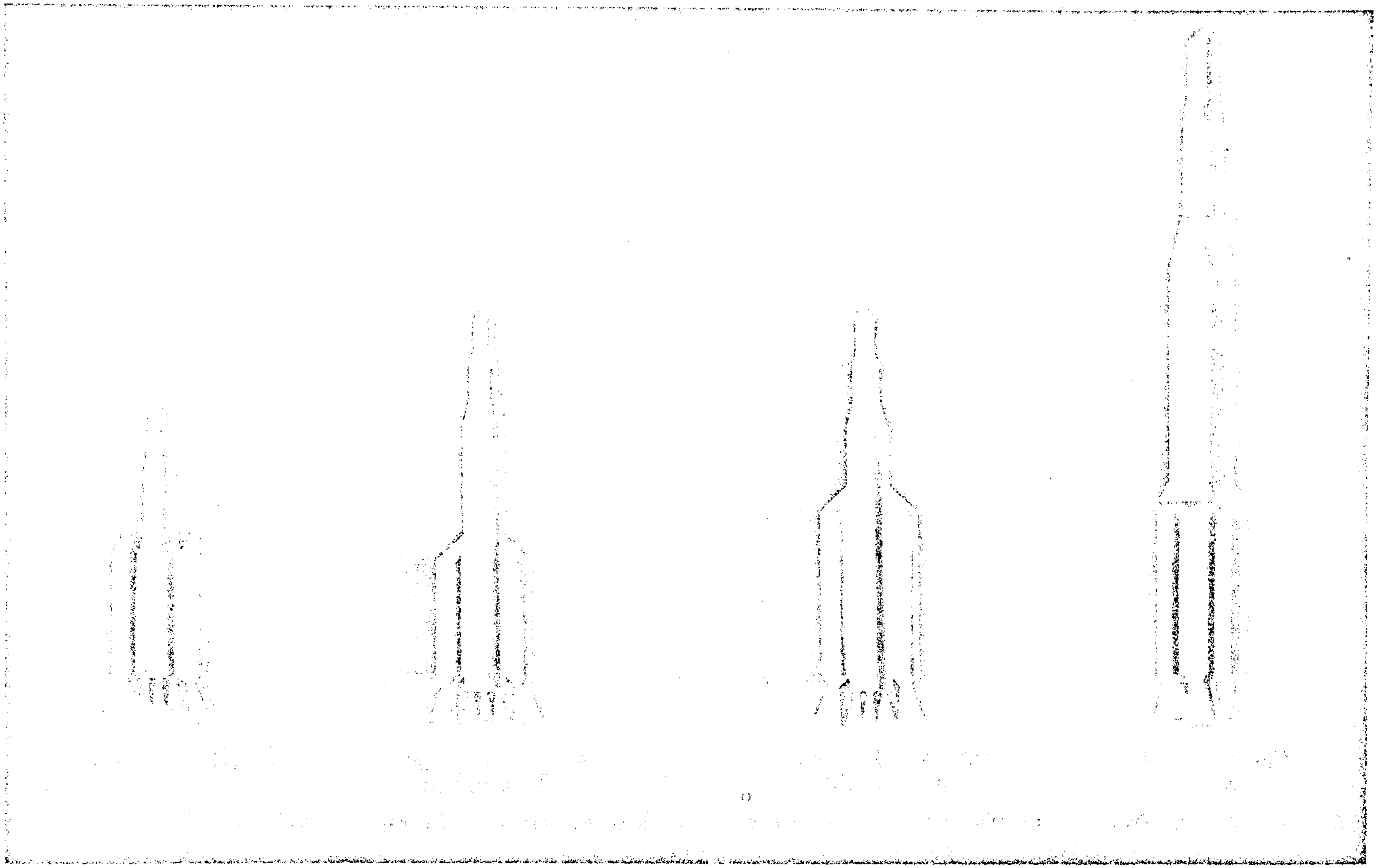
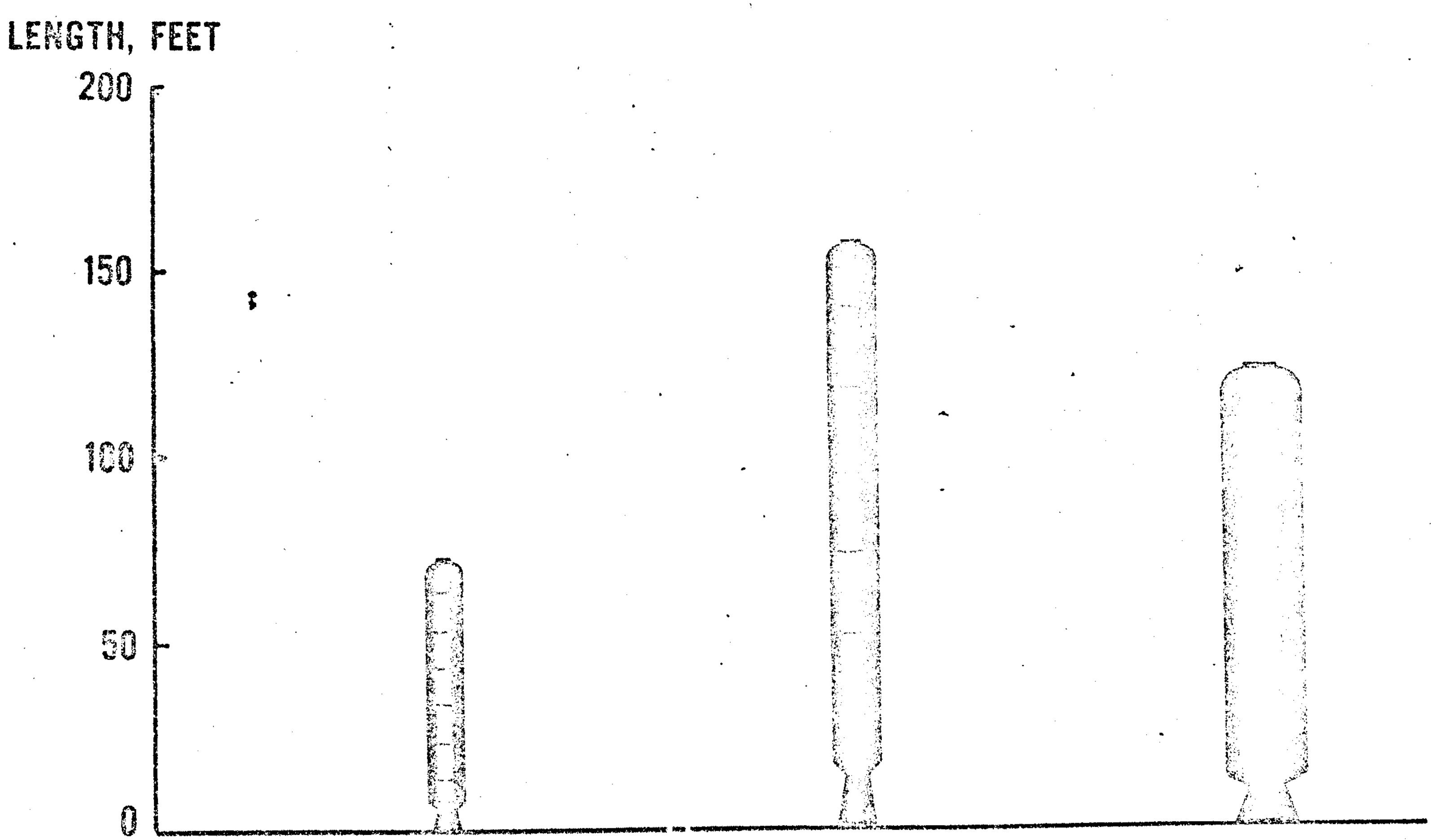


Figure 6

COMPARISON OF SOLID MOTORS

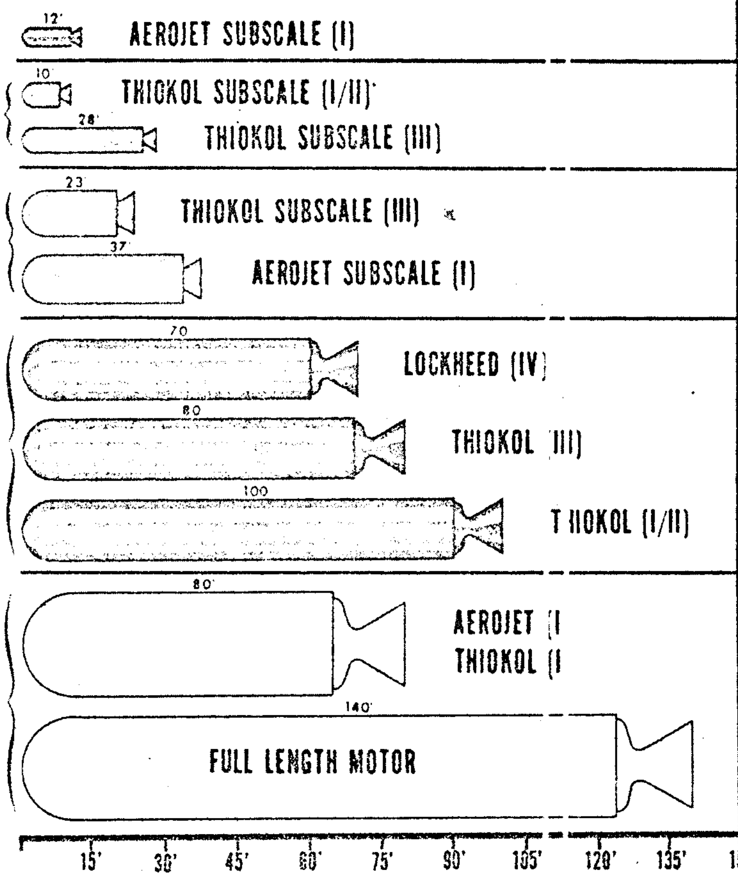


PROPELLANT WT.	400,000 LBS.	1.5 MILLIONS LBS.	3.1 MILLION LBS
THRUST	ABOUT 1 MILLION	3.0 MILLION LBS	6.0 MILLION LBS
BURNTIME	ABOUT 100 SECONDS	120 SECONDS	120 SECONDS

ML62-582

MOTOR SUMMARY

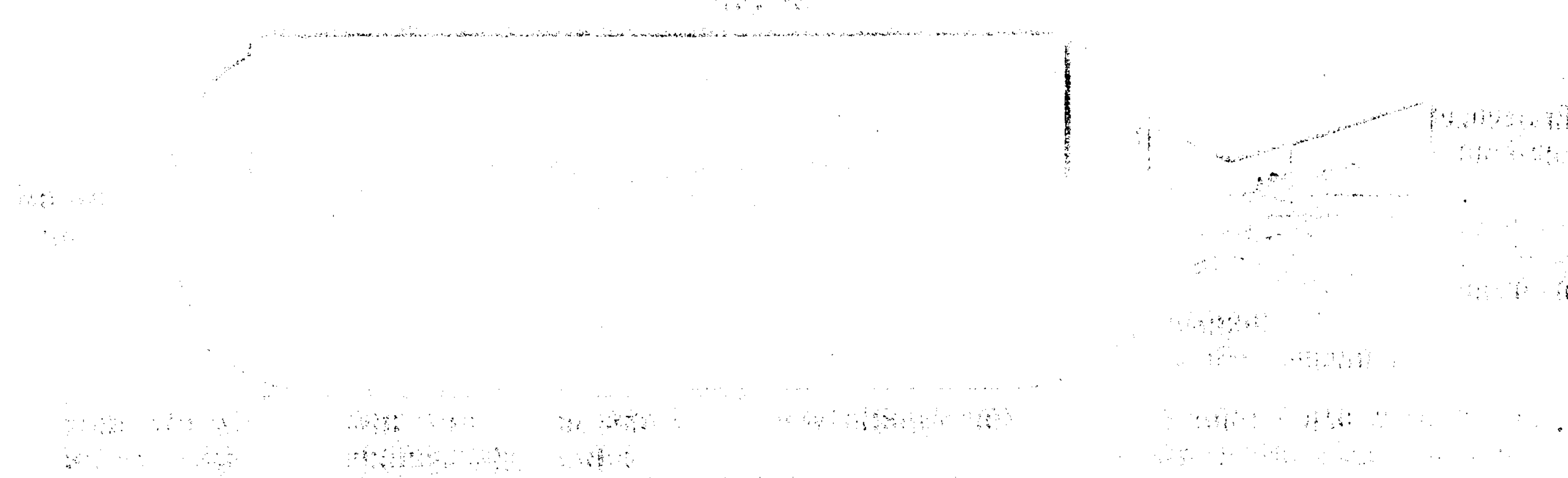
LARGE SOLID MOTOR PROGRAM



MOTOR DIAMETER	MOTOR	NO. TESTS	THRUST (LBS)	DURATION (SEC)	WEIGHT (LBS)	TEST DATES
44"	AEROJET SUBSCALE (I)	4	82,000	20	9,000	(3) 6/64, 8/64
65"	THIOKOL SUBSCALE (I/II)	4	45,000	50	11,000	3/,4/,9/,10/64
65"	THIOKOL SUBSCALE (III)	2	190,000	60	65,000	1/64, 4/64
120"	THIOKOL SUBSCALE (III)	1	170,000	130	120,000	6/64
120"	AEROJET SUBSCALE (I)	1	625,000	70	230,000	8/64
156"	LOCKHEED (IV)	2	870,000 1,100,000	110 135	490,000 700,000	5/64 10/64
156"	THIOKOL (III)	1	1,400,000	120	750,000	11/64
156"	THIOKOL (I/II)	1	3,370,000	<60	900,000	8/64
260"	AEROJET (I	2	3,250,000	<120	1,840,000	2/65 7/65
260"	THIOKOL (I	2	3,250,000	<120	1,770,000	1/65 6/65
260"	FULL LENGTH MOTOR	2	7,000,000	120	3,500,000	1966 1967

Figure 8

260 SL-1 MOTOR



MOTOR WEIGHT ____________ 1,700,000 LB

AVERAGE THRUST ________ OVER 3,000,000 LB

TRANSPORTING LARGE SEGMENTS

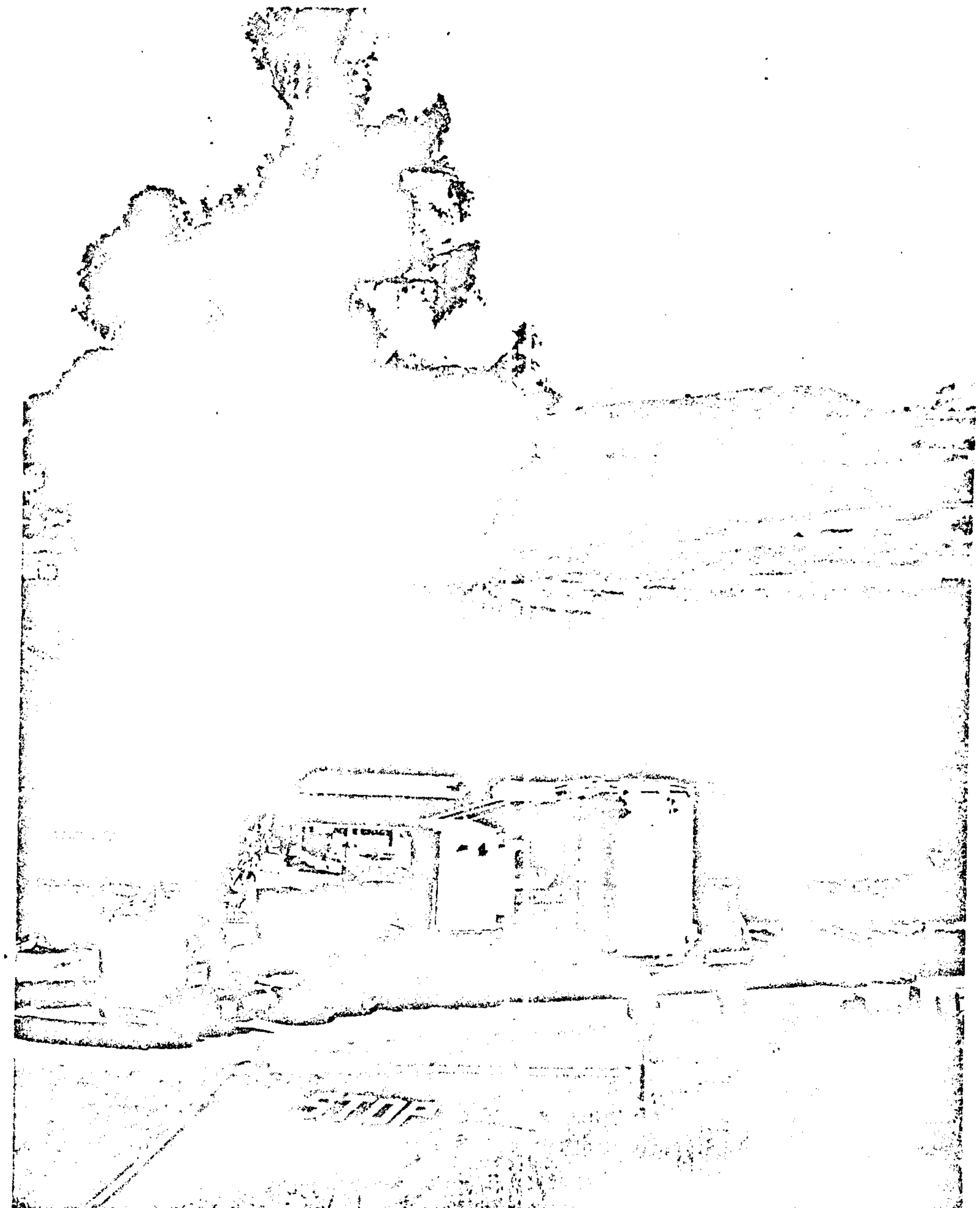


Figure 10

HANDLING EQUIPMENT FOR LARGE SEGMENTS

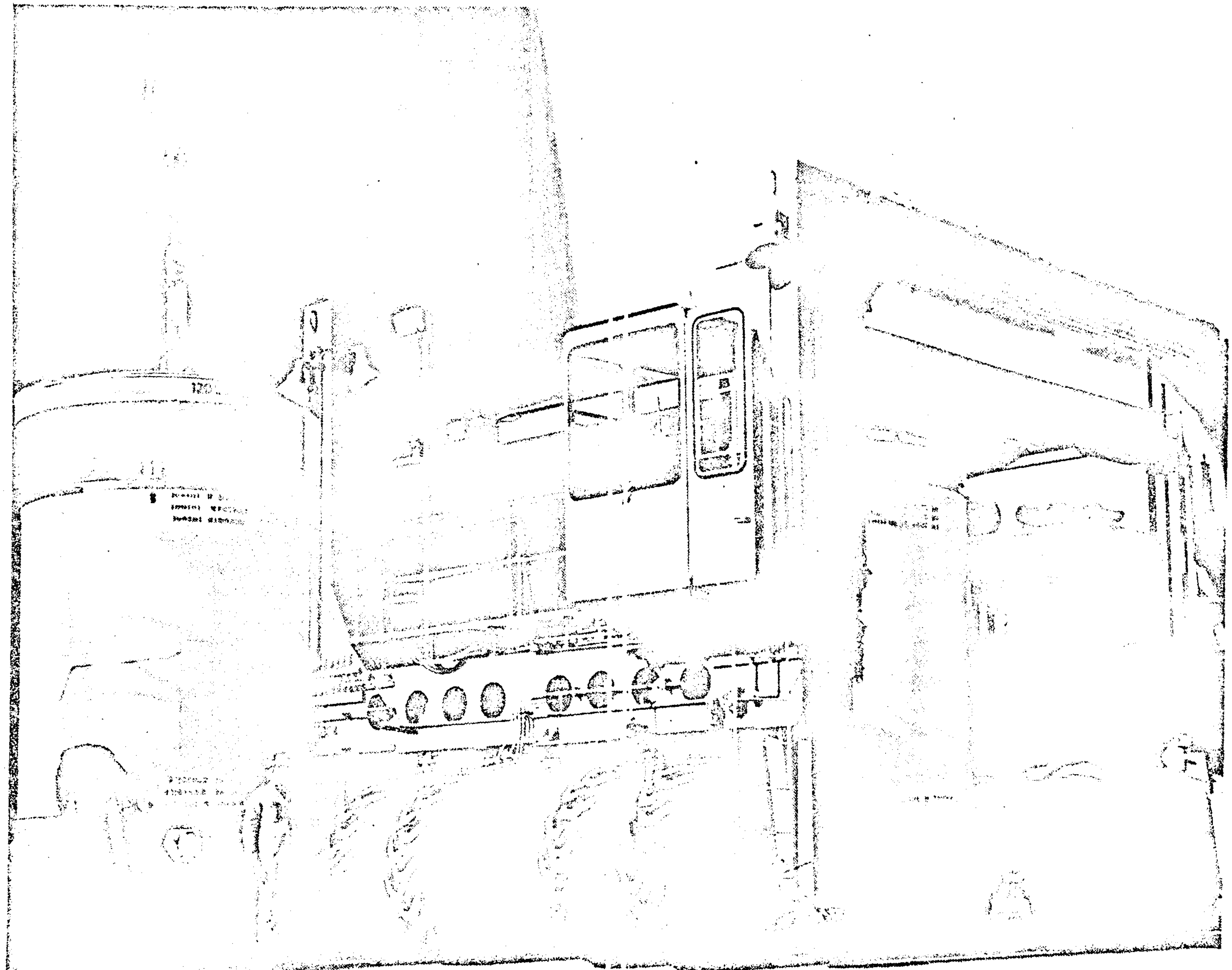
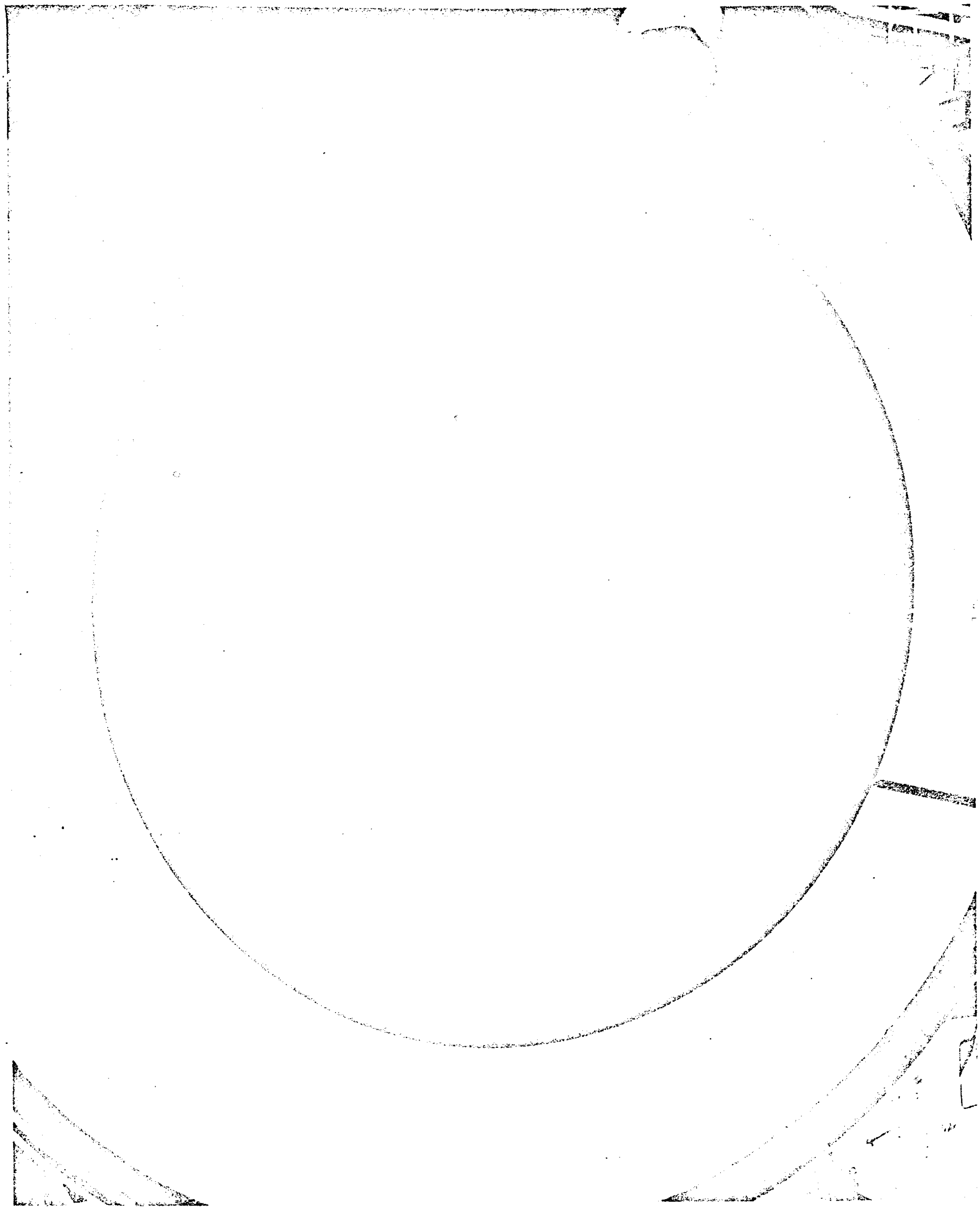
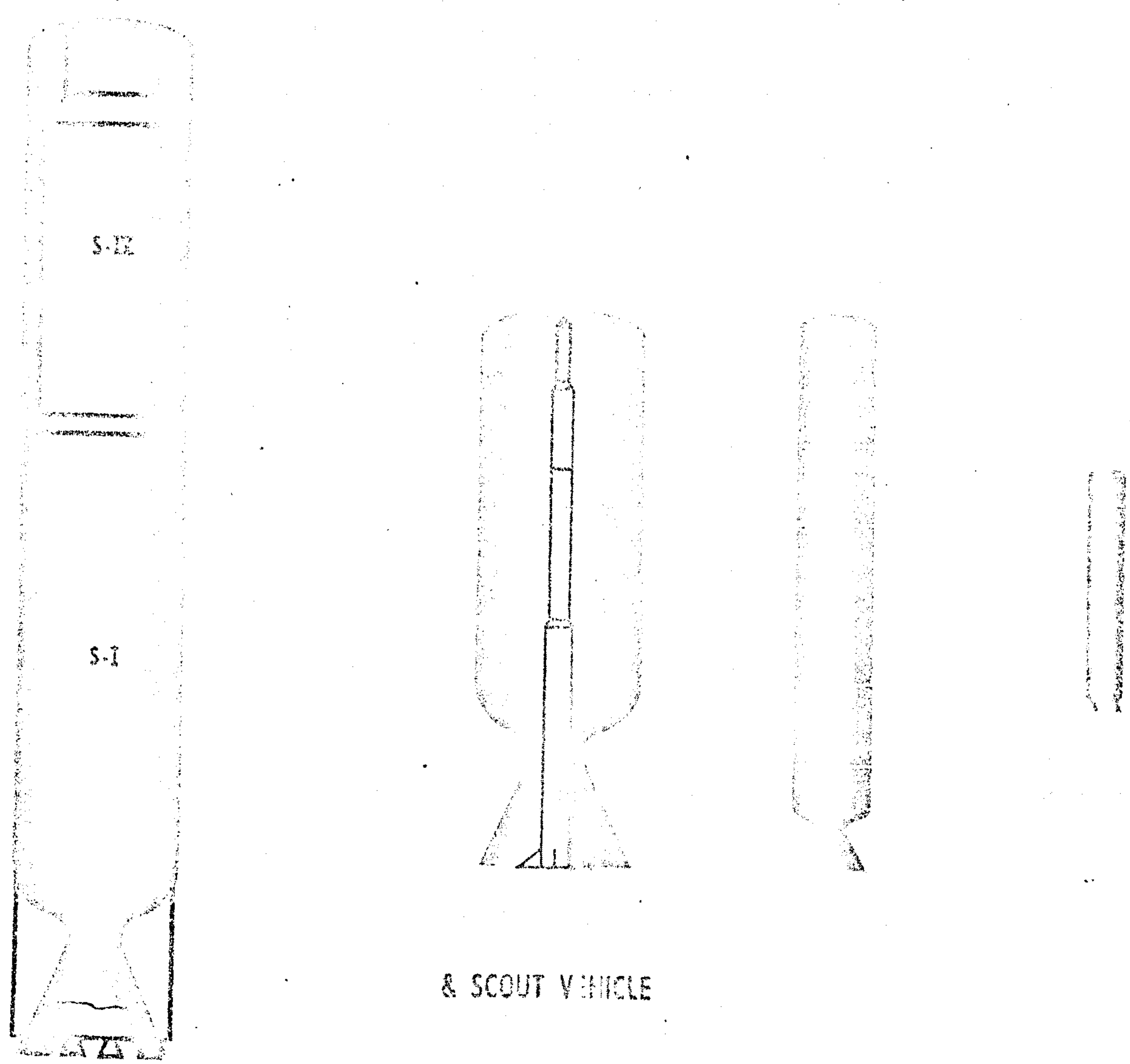


Figure 11

Figure 12





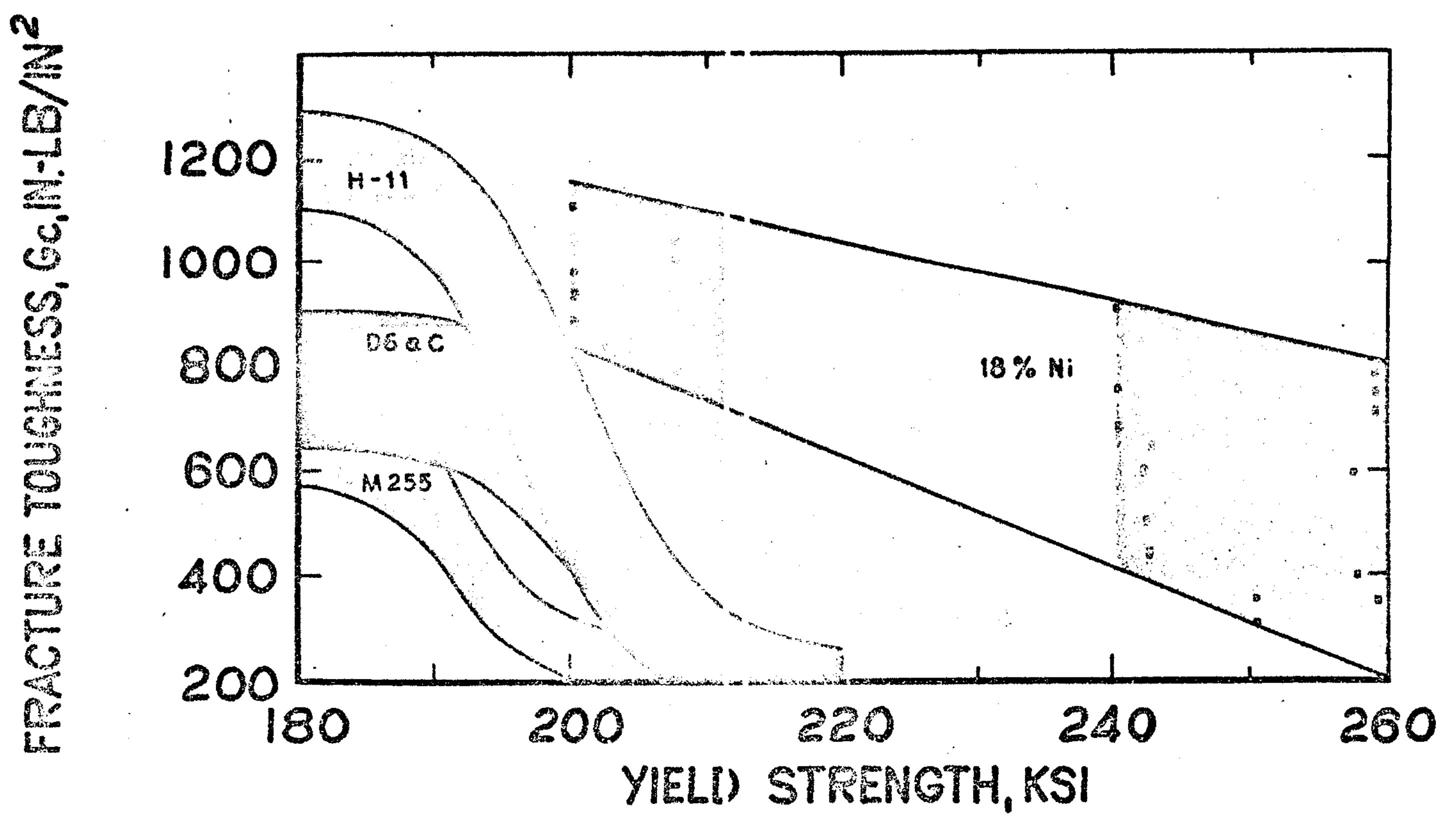
& SATURN I STAGE

& SCOUT VEHICLE

Figure 13

LARGE SOLID BOOSTER ROCKET

FRACTURE TOUGHNESS OF 18% NICKEL MARAGING STEEL



FRACTURE TOUGHNESS VS YIELD STRENGTH FOR VARIOUS STEELS

Figure 14

LARGE SOLID BOOSTER ROCKET

STEEL CASE MATERIALS COMPARISON
MARAGING VS D6AC, AF-255 & 4340

FACTORS	COMPARISON	REASON
DESIGN		
WEIGHT	SUPERIOR	HIGHER STRENGTH (220,000 VS 190,000 PSI YLD)
GROWTH POTENTIAL	SUPERIOR	LABORATORY EVIDENCE (260,000 PSI YLD POTENTIAL)
MANUFACTURING		
FORMABILITY	COMPARABLE	COMPARABLE PHYSICAL PROPERTIES
MACHINABILITY	SUPERIOR	LESS MACHINING AT HARDENED STATE
WELDABILITY	SUPERIOR	NO PRE-HEAT OR POST-HEAT
DIMENSIONAL CONTROL	SUPERIOR	NO HEAT-TREAT DISTORTION (ELIMINATES SIZING)
HEAT TREAT	SUPERIOR	NO HIGH TEMPERATURE OR QUENCH
REPAIRABILITY	SUPERIOR	WELD REPAIRS LOCALLY RE-AGED
COST		
MATERIAL	HIGHER	LIMITED QUANTITIES TO DATE
FABRICATION	COMPARABLE	MATERIAL COST OFFSET BY MFG CONSIDERATIONS
TOOLING	SUPERIOR	NO HEAT TREAT TOOLING - LESS WELD TOOLING
FACILITIES	SUPERIOR	NO NEW HEAT TREAT FACILITIES
EXPERIENCE	LESS	LIMITED EXPERIENCE ON HIGH THICKNESS
AVAILABILITY	LESS	MARAGING STEEL COMMERCIALLY AVAILABLE

Figure 15

LARGE SOLID BOOSTER ROCKET
260-IN.-DIA MOTOR CASE FABRICATION

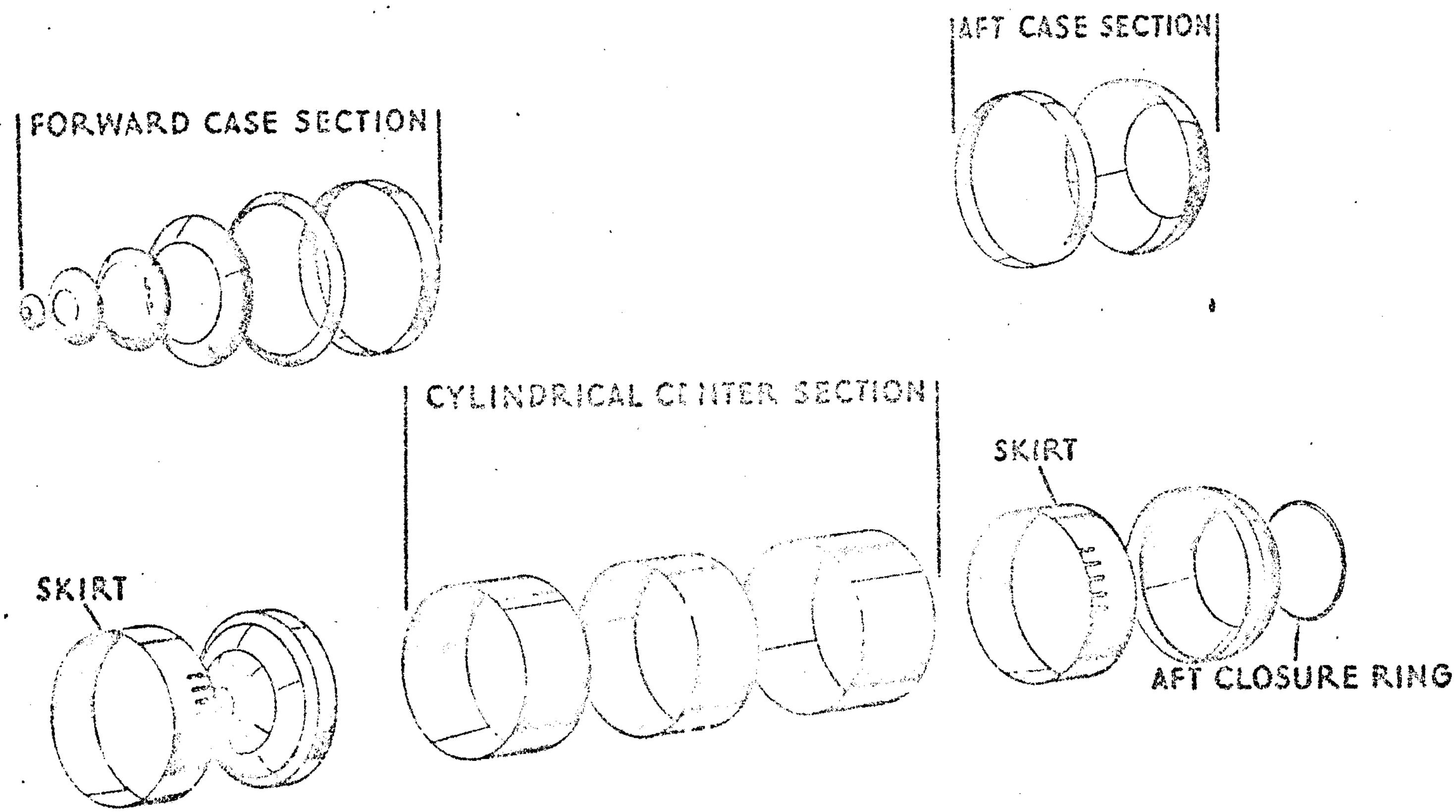
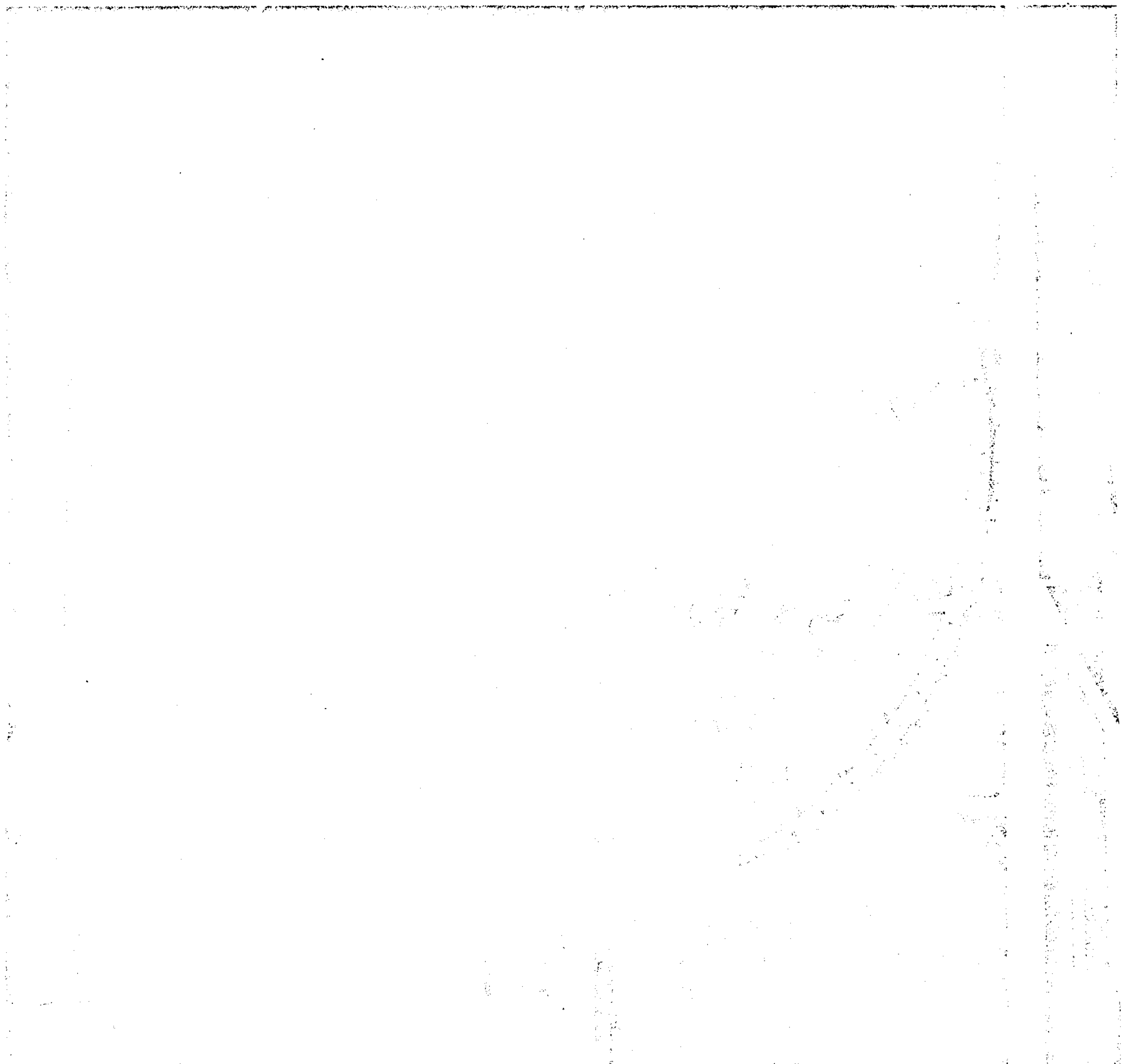


Figure 16



260-INCH MILD STEEL CYLINDER POSITIONED ON SEAMER

Figure 17

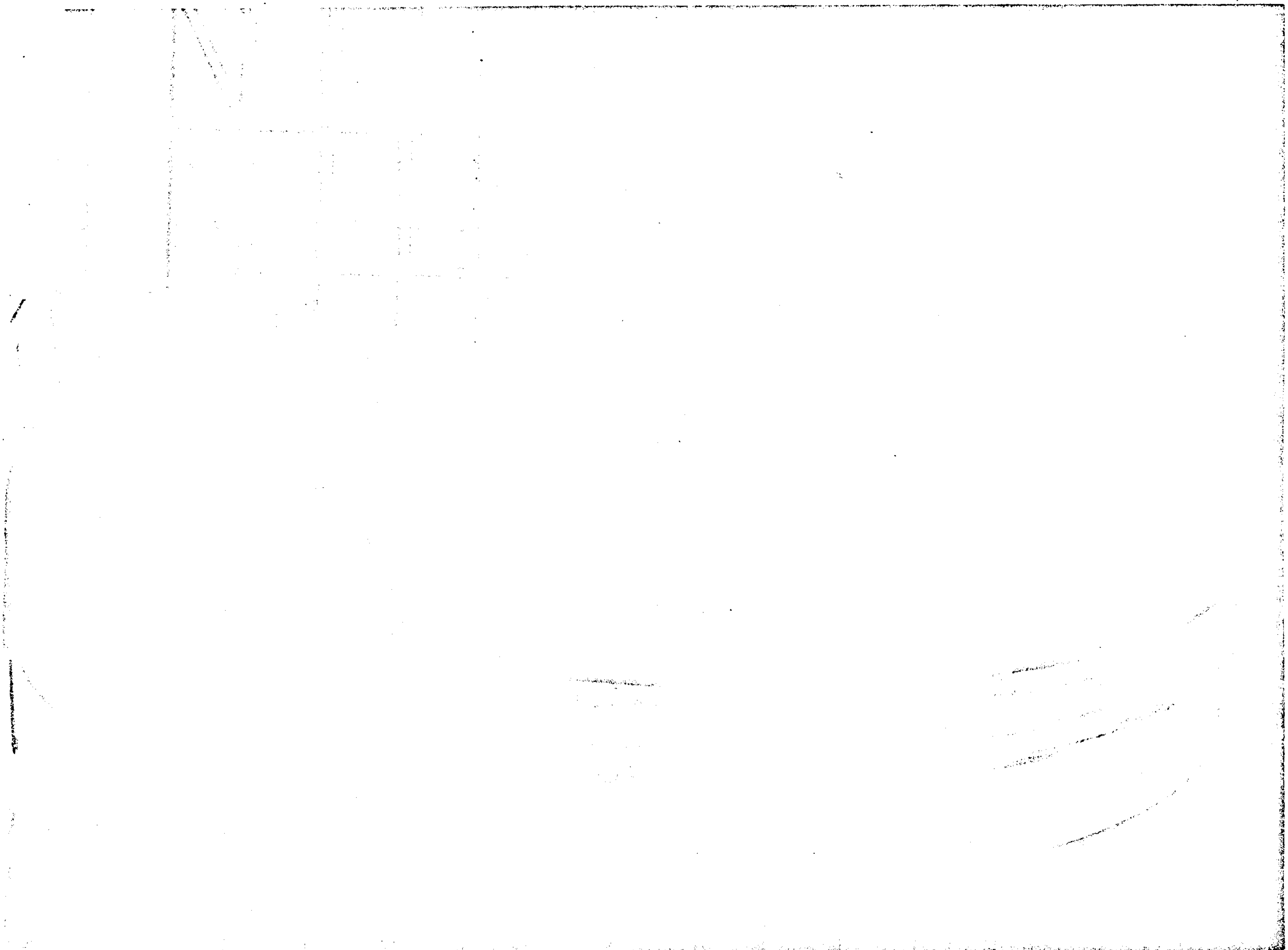
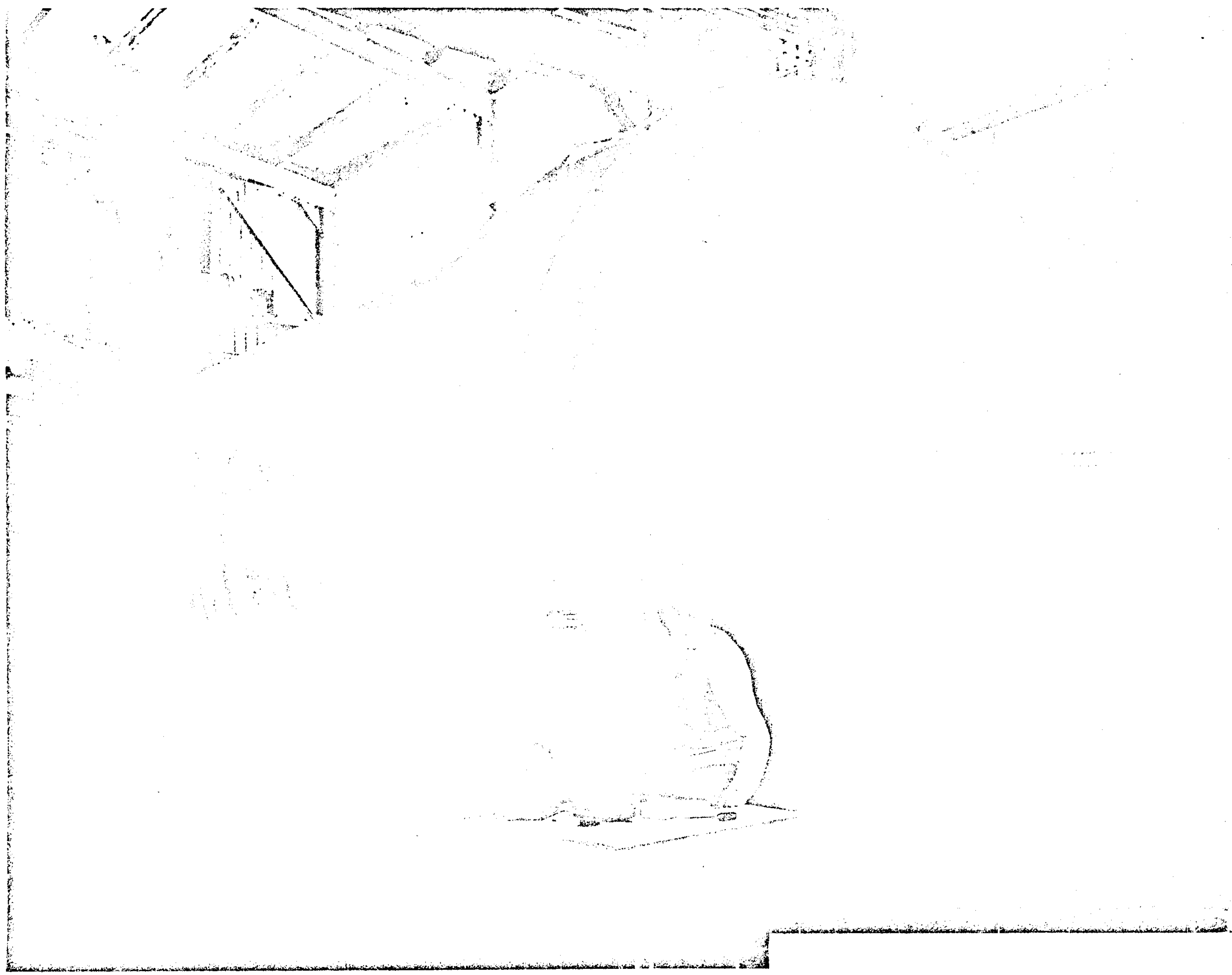
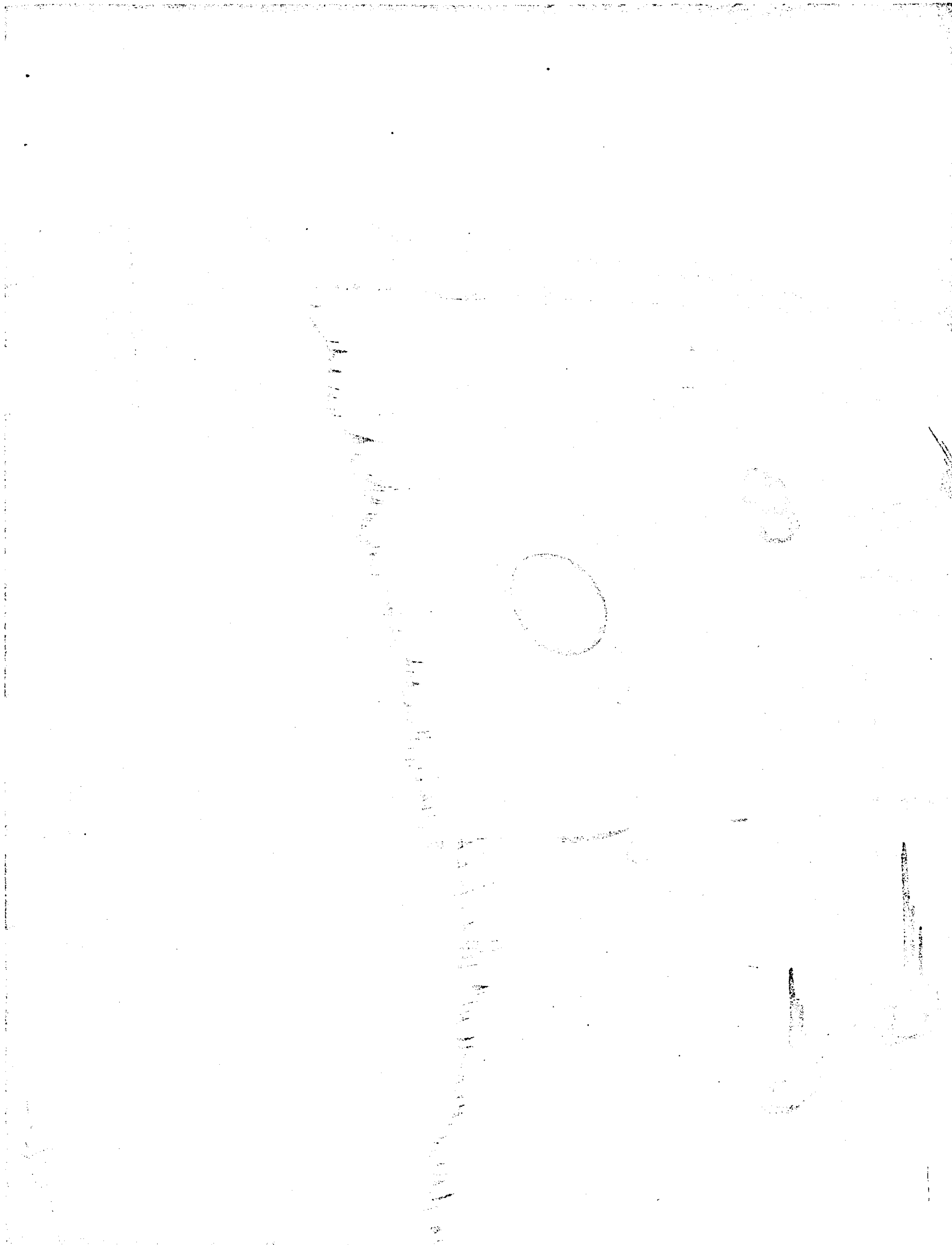


Figure 18



F'gure 19



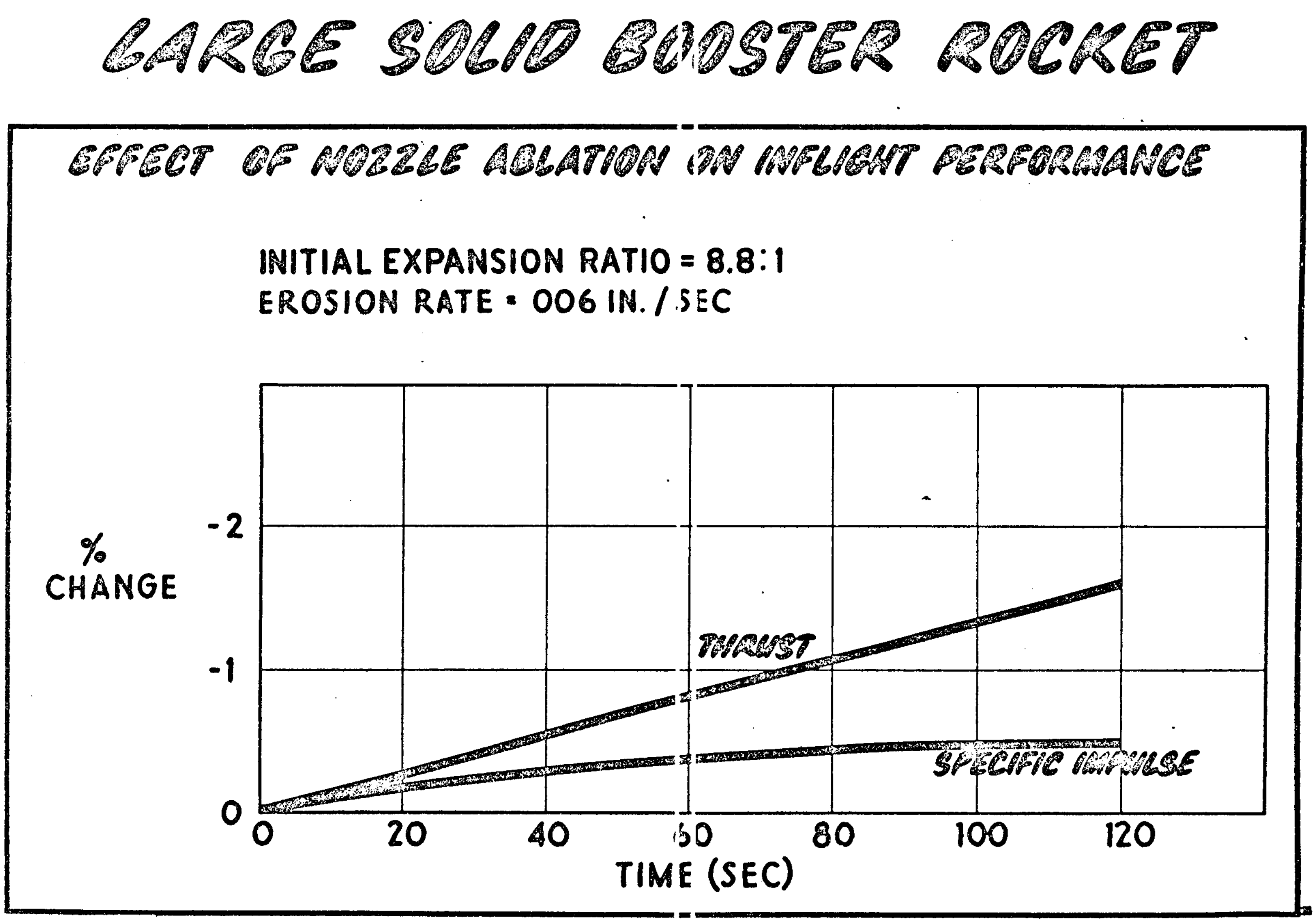
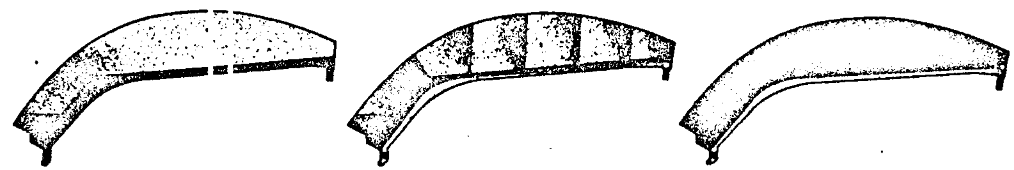

LARGE SOLID BOOSTER ROCKET
EFFECT OF NOZZLE ABLATION ON INFLIGHT PERFORMANCE
INITIAL EXPANSION RATIO = 8.8:1
EROSION RATE = 006 IN./SEC
%
CHANGE
-2
-1
0
0
20
40
60
80
100
120
TIME (SEC)
THRUST
SPECIFIC IMPULSE

Figure 21

LARGE SOLID BOOSTER ROCKET

NOZZLE MATERIAL—260" DIA MOTOR



CHARACTERISTICS	MONOLITHIC GRAPHITE	SEGMENTED GRAPHITE	ABLATIVE
AVAILABILTY-MONTHS	18-24	6	6
COST	LOW	MEDIUM	HIGH
EROSION RATE in/sec	.002-.003	.002-.003	.004-.008
TEMPERATURE GRADIENT STRESS RESISTANCE	LOW	GOOD	EXCELLENT
EXPERIENCE	EXTENSIVE	LIMITED	LIMITED

Figure 22

260" D MOTOR NOZZLES

	THROAT D	EXIT D	WEIGHT
1/2 LENGTH MOTOR:	65 IN	220 IN	30,000 LBS
FULL LENGTH MOTOR:	90 IN	260 IN	50,000 LBS

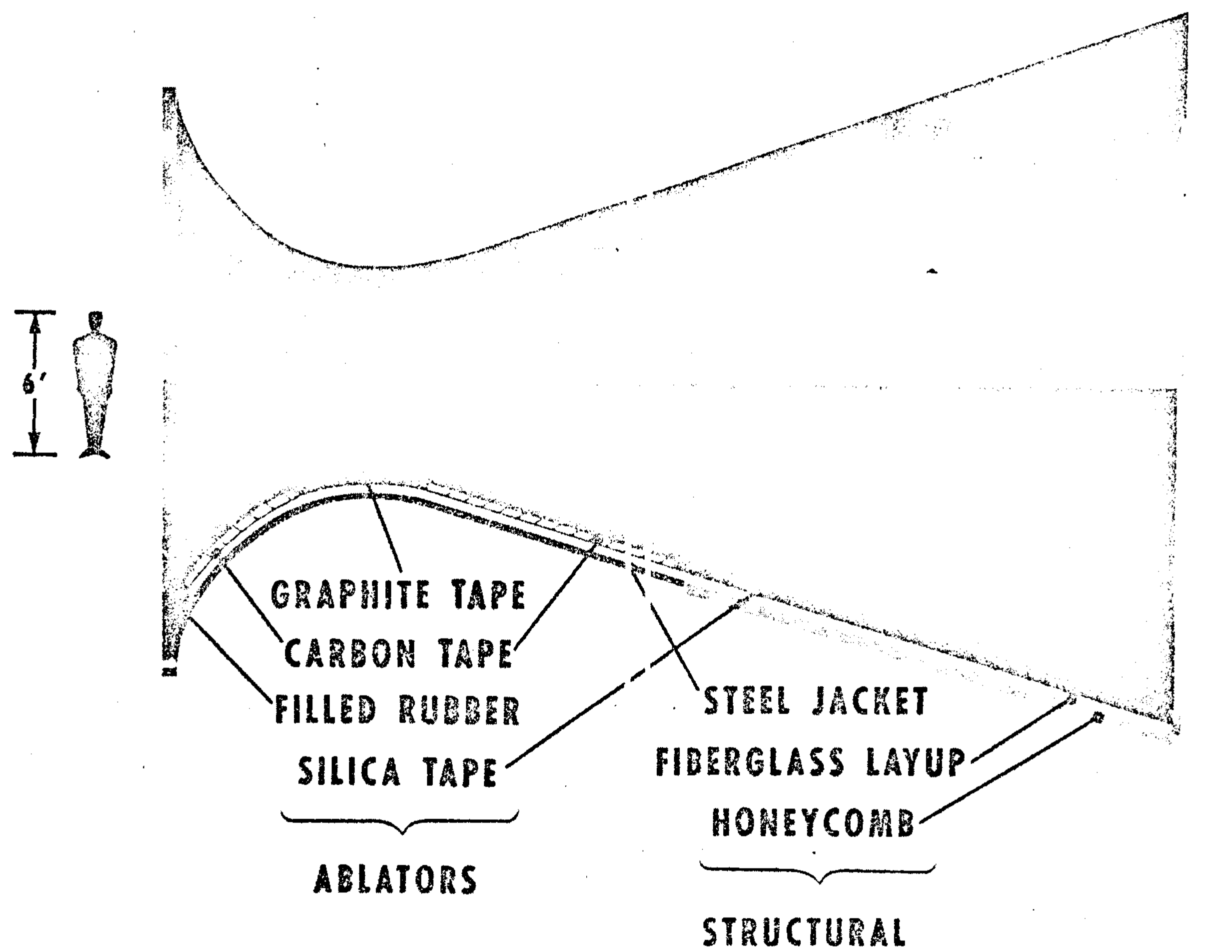


Figure 23

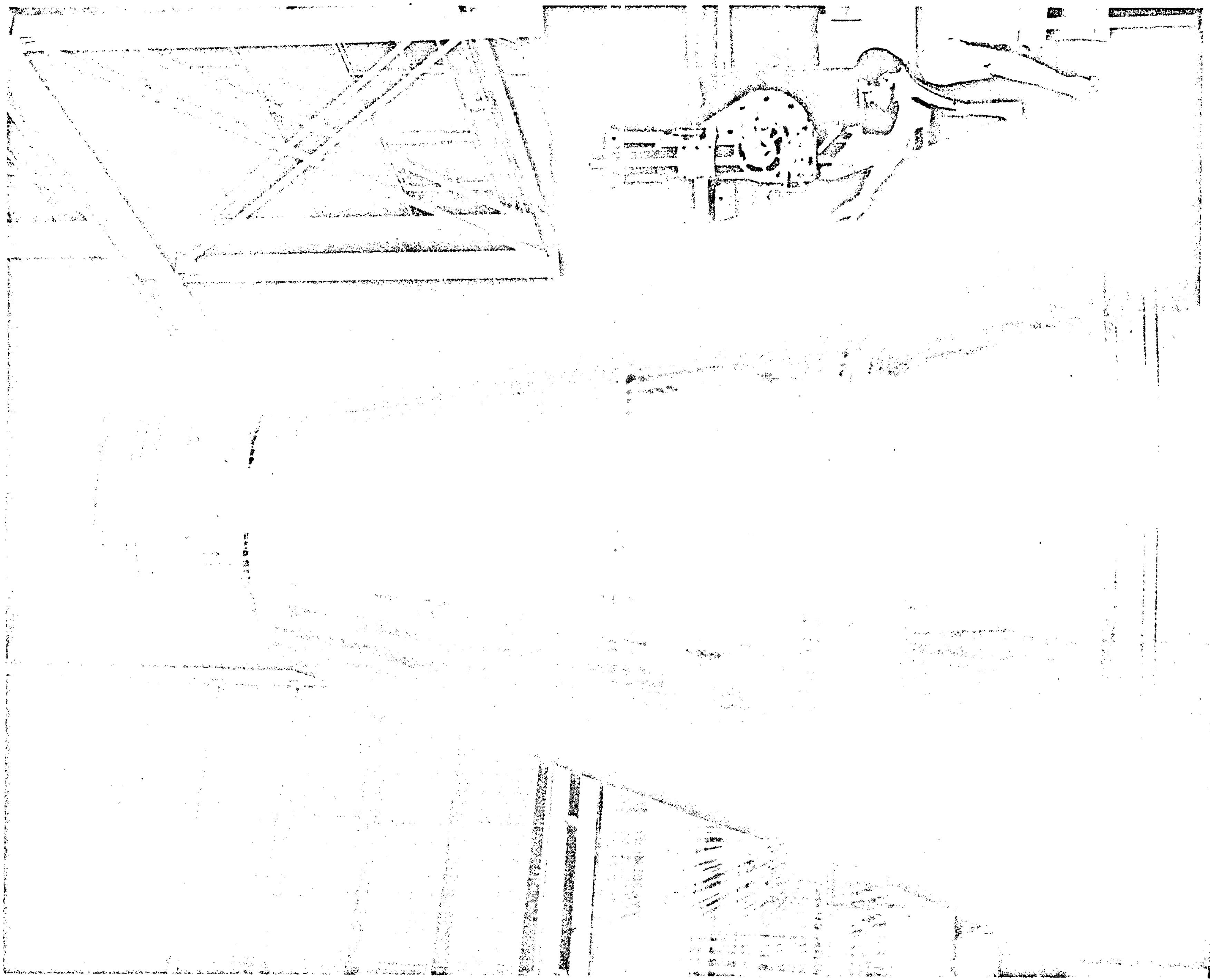


Figure 24

SILICA WRAPPING - NOZZLE EXTENSION

NASA RP64 - ~~1342~~ - 1413
(-1342 changed to -1413 on 4-30-64)

Figure 25

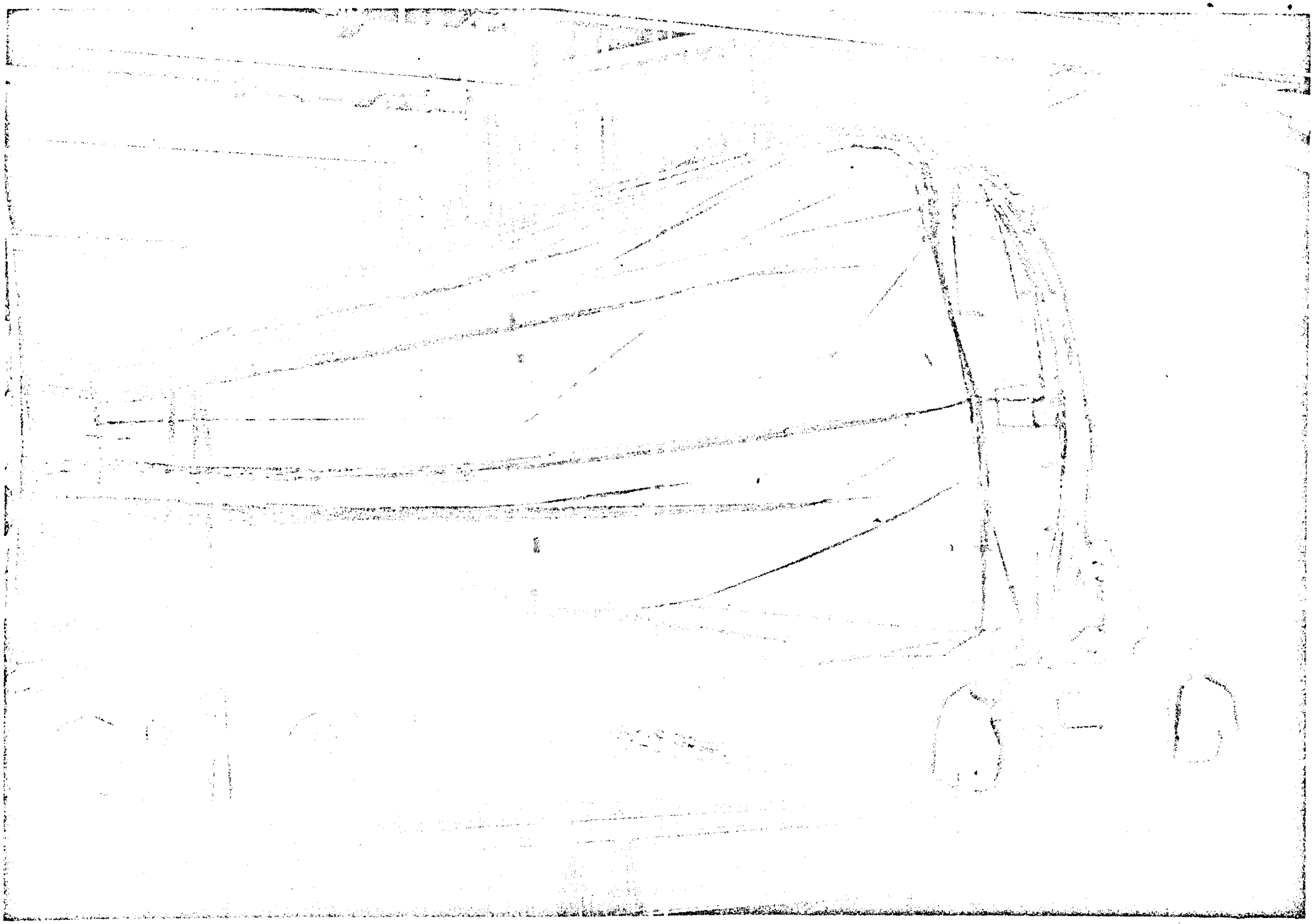
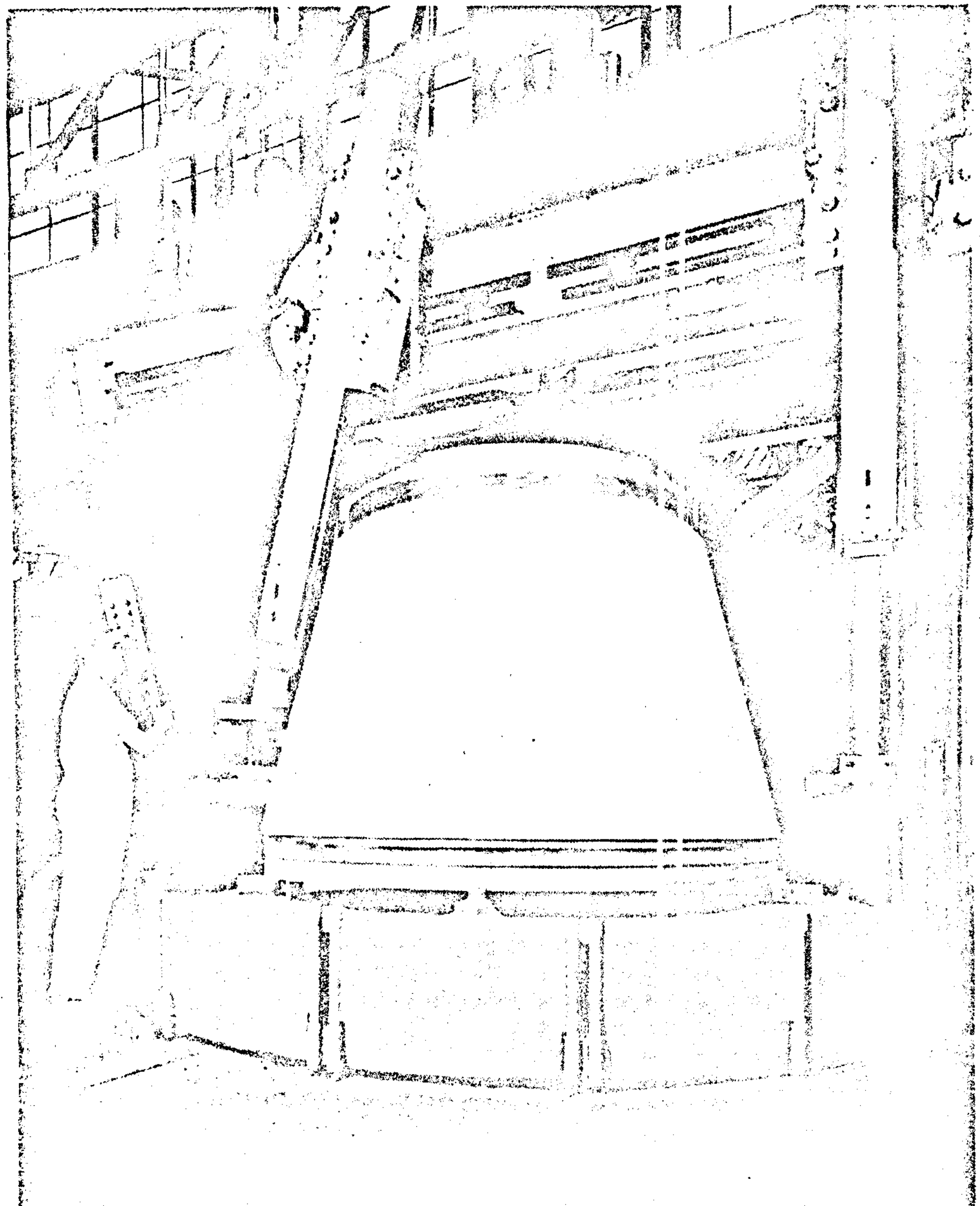


Figure 26

EXIT CONE WITH VACUUM BAG GOING INTO AUTOCLAVE
FOR VACUUM BAG CURING



MACHINING SILICA LINER - NOZZLE EXTENSION

NASA RP64-1343

Figure 27

INSERTING ABLATIVE LINER IN ROCKET ENGINE NOZZLE

NASA RP64-1075

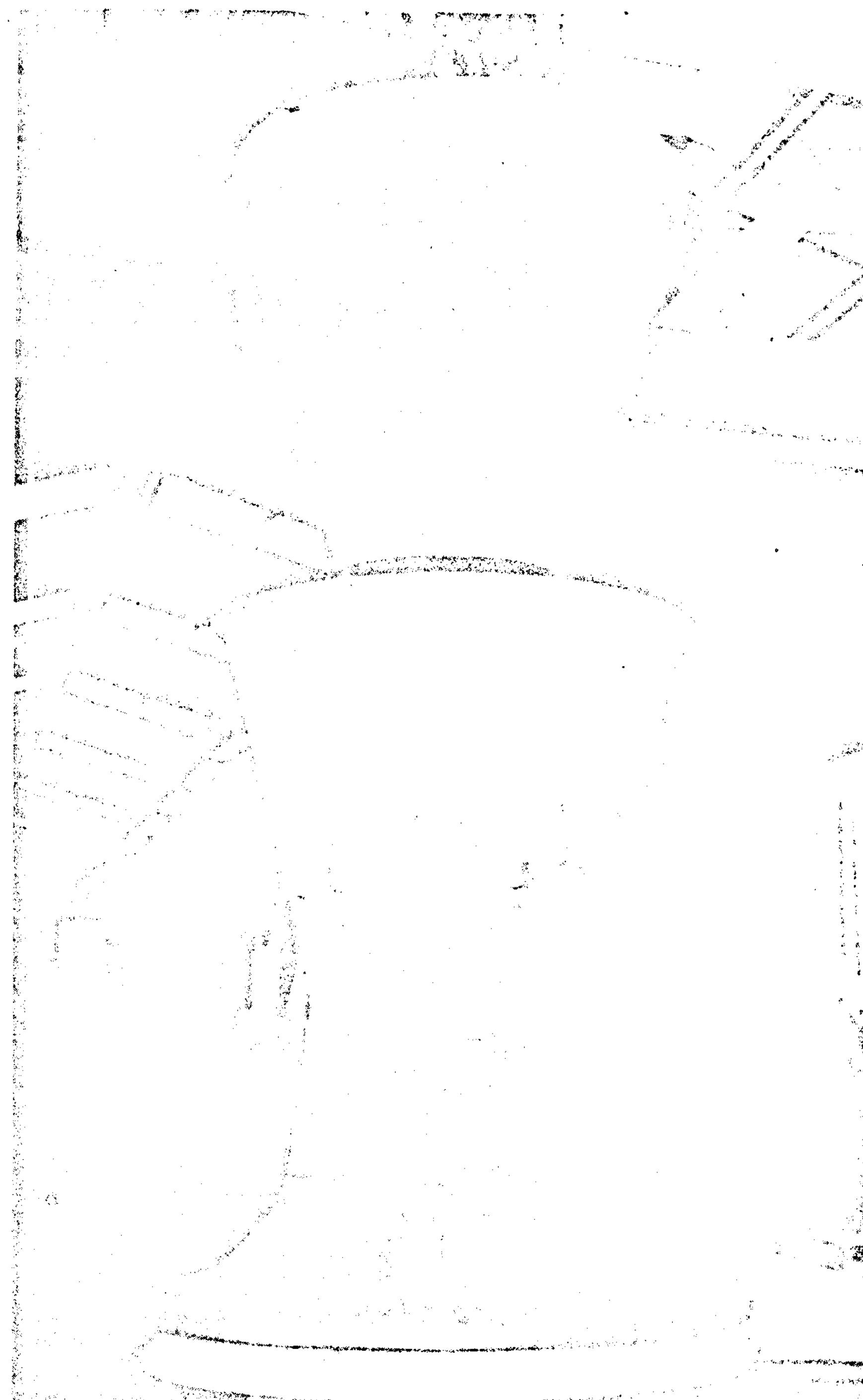
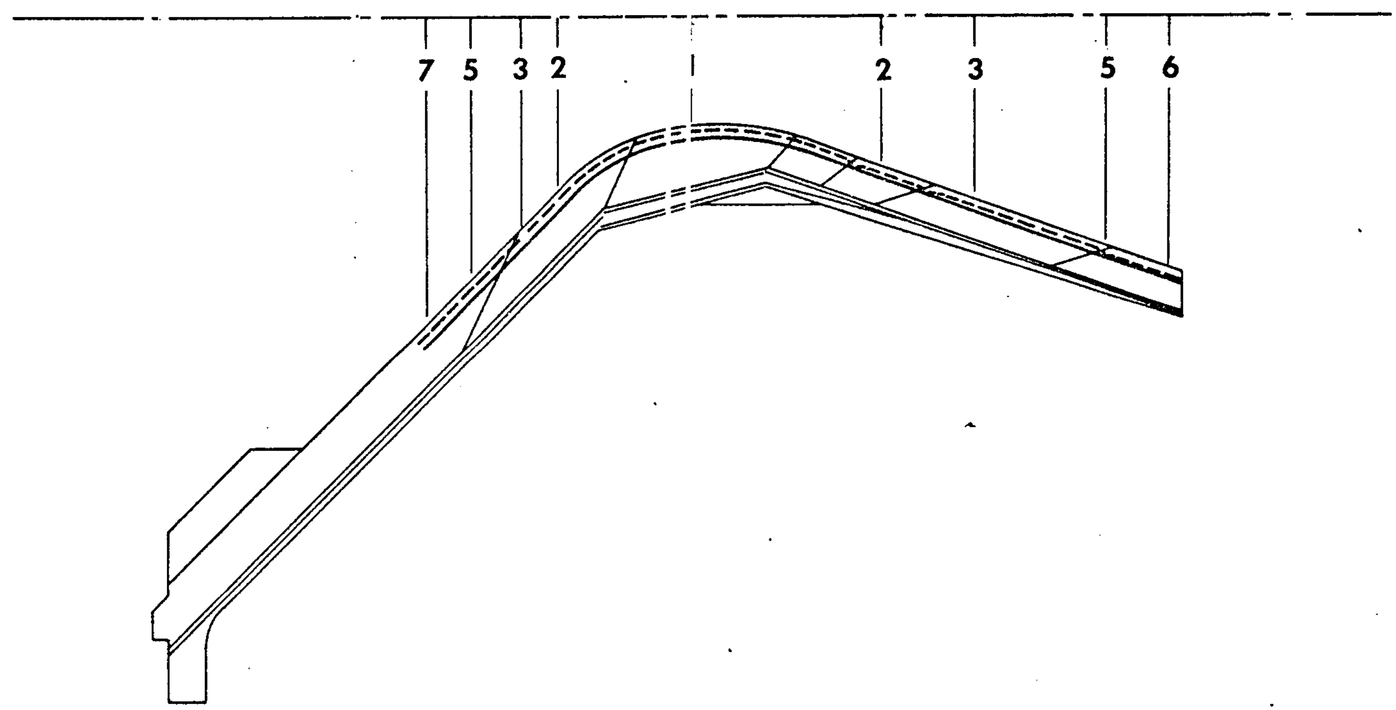


Figure 2

65-SS-2 NOZZLE PERFORMANCE



AREA RATIOS	7	5	3	2	1	2	3	5	6
—— PREDICTED EROSION DEPTH, INCH	.19	.21	.24	.29	.38	.24	.25	.25	.40
---- AVERAGE EROSION DEPTH, INCH	.08	.08	.13	.18	.28	.04	.10	.11	.37

Figure 29

LARGE SOLID BOOSTER ROCKET

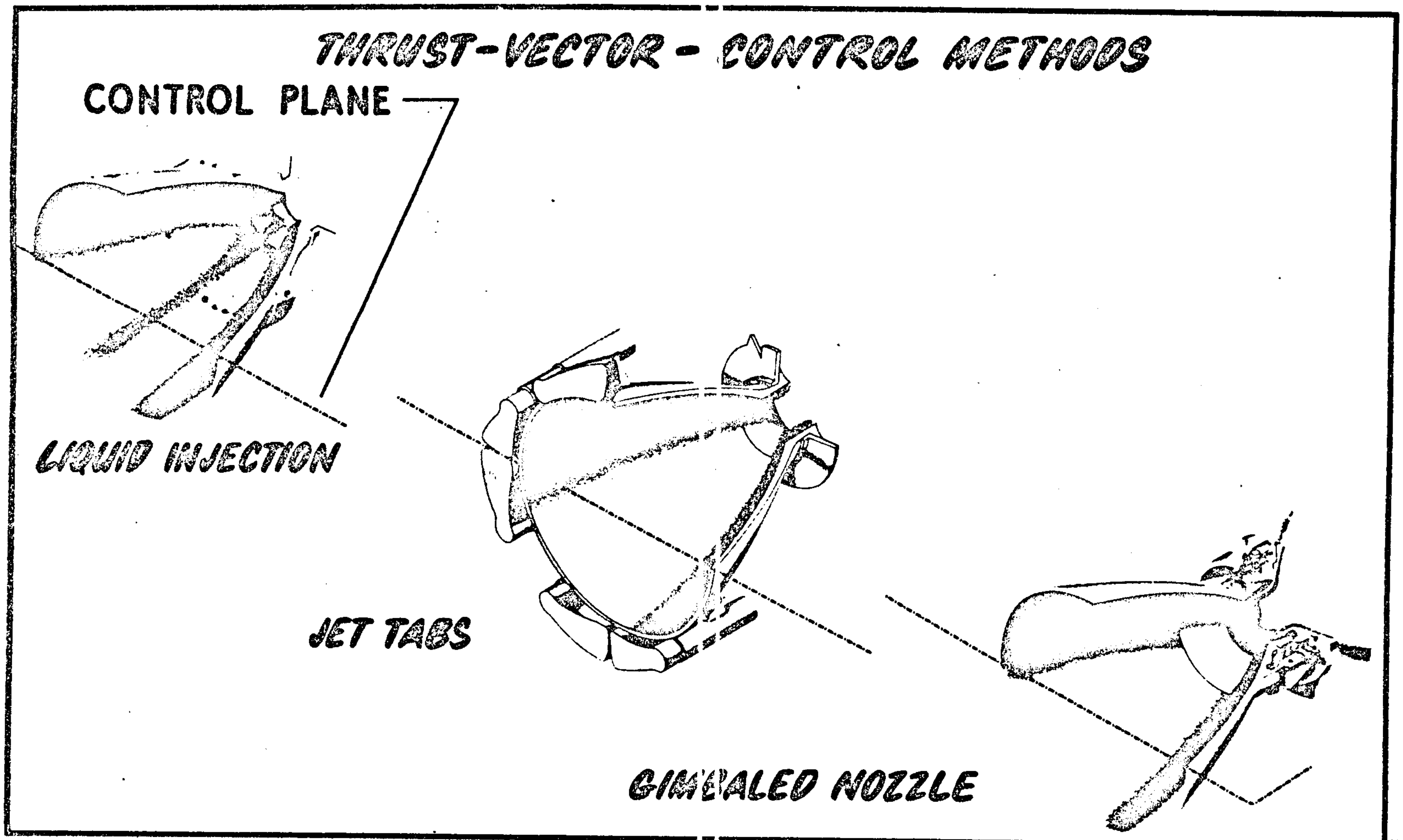


Figure 30

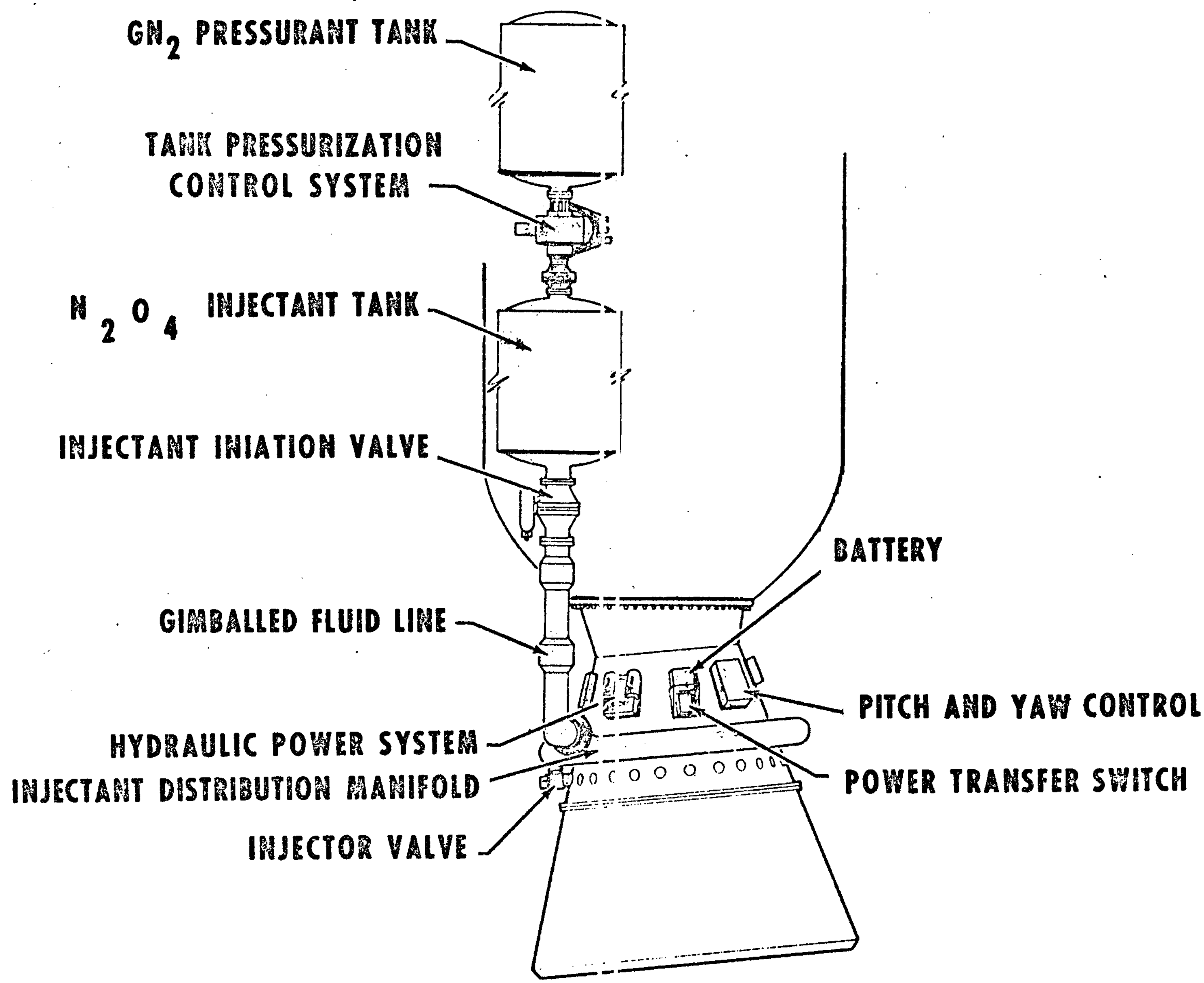

GN$_2$ PRESSURANT TANK
TANK PRESSURIZATION CONTROL SYSTEM
N$_2$O$_4$ INJECTANT TANK
INJECTANT INIATION VALVE
GIMBALLED FLUID LINE
HYDRAULIC POWER SYSTEM
INJECTANT DISTRIBUTION MANIFOLD
INJECTOR VALVE
BATTERY
PITCH AND YAW CONTROL
POWER TRANSFER SWITCH

Figure [illegible]

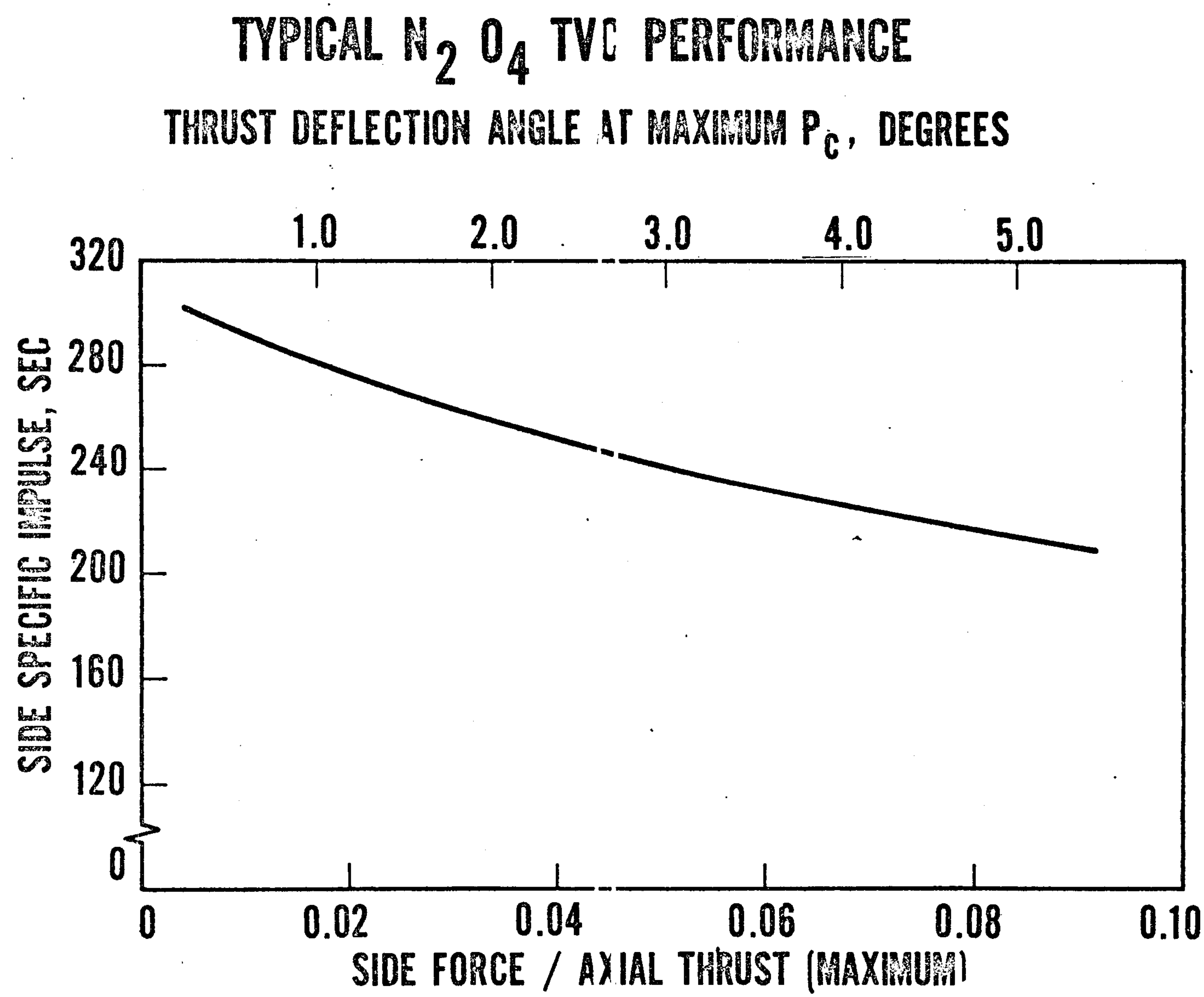
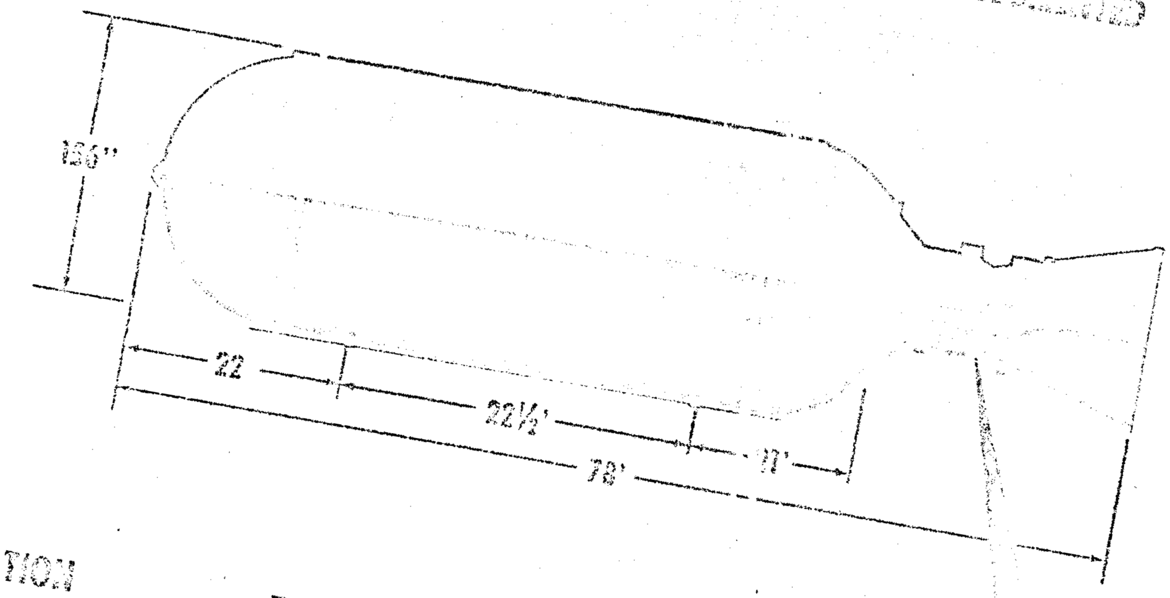

TYPICAL N_2O_4 TVC PERFORMANCE
THRUST DEFLECTION ANGLE AT MAXIMUM P_C, DEGREES
1.0
2.0
3.0
4.0
5.0
320
280
240
200
160
120
0
SIDE SPECIFIC IMPULSE, SEC
0
0.02
0.04
0.06
0.08
0.10
SIDE FORCE / AXIAL THRUST (MAXIMUM)

Figure 32

Figure 33

PROGRAM III: THIOKOL

156" D [illegible] - GIMBAL NOZZLE - SEGMENTED



DESIGNATION	TU-412
NO. TESTS	1
THRUST	1,400,000 LBS
DURATION	120 SEC
CHAMBER PRESSURE	700 PSI
THROAT DIAMETER	38"
TOTAL WEIGHT	730,000 LBS

Figure 34

VEHICLE CONTROL REQUIREMENTS

	PAYLOAD 125K		PAYLOAD 500K	
	W/FINS	W/O	W/FINS	W/O
MAX NOZZLE DEFL - δ DEG	1.2	4	1.2	4
MAX NOZZLE VEL - δ DEG/SEG	4.45	26.6	3.34	20
MAX NOZZLE ACCEL - δ RAD/SEG^2	.98	5.83	.55	3.28
SERVO BREAK FREQ - CPS	2.0	2.0	1.5	1.5
NOM VEHICLE CONT FREQ - CPS	.25	.25	.18	.18
CONTROL SIDE IMPULSE - %	1.87	2.33	1.91	2.26
MAX HINGE MOMENT (W/SKIRTS) - IN LB X 10^{-6}	.801	1.012	4.912	6.665

Figure 35

BASIC CAST, CURE, AND TEST FACILITY

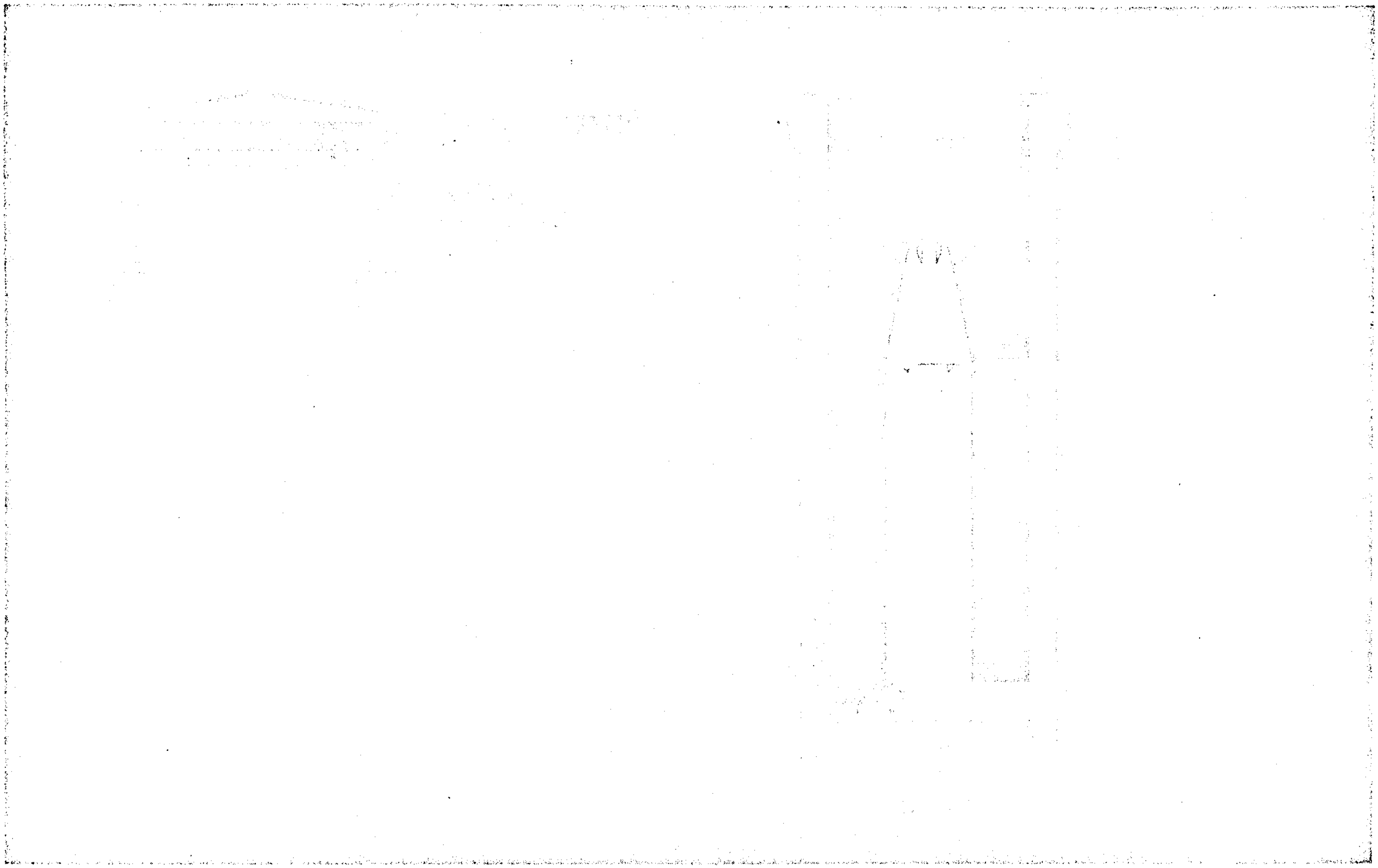
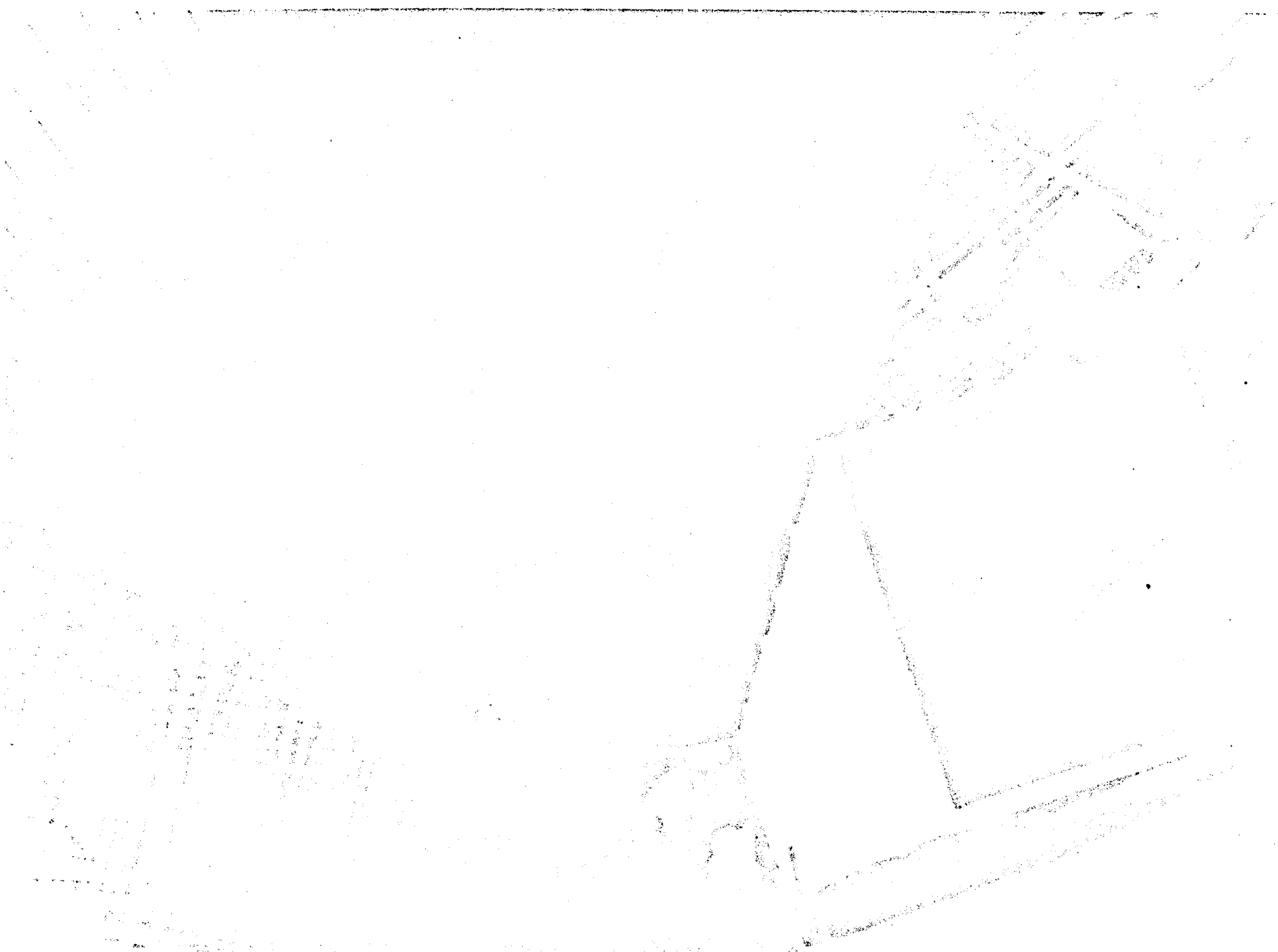


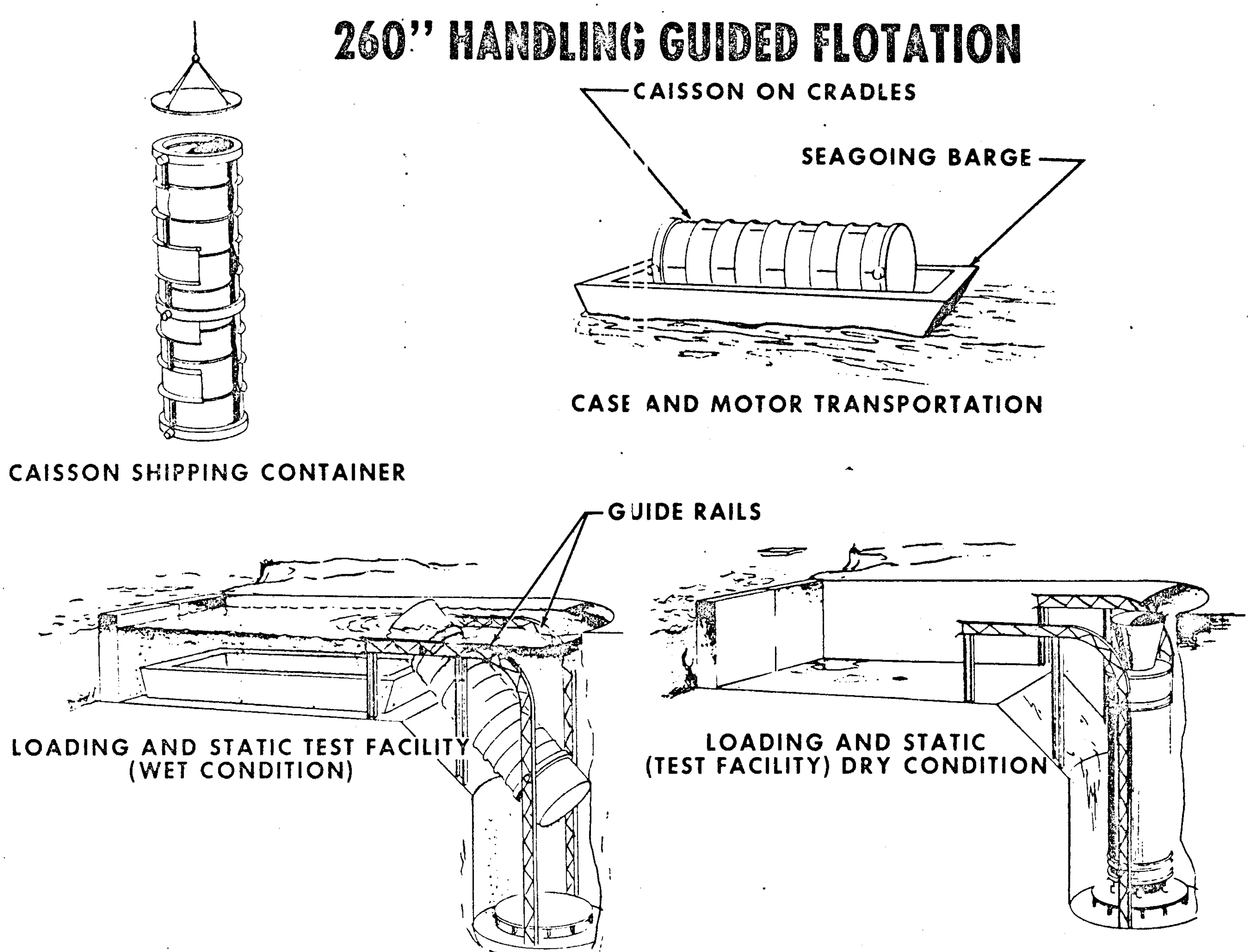
Figure 36

NASA RF64-1020



LOOKING DOWN INTO CAST-TEST PIT

Figure 37



260" HANDLING GUIDED FLOTATION
CAISSON ON CRADLES
SEAGOING BARGE
CASE AND MOTOR TRANSPORTATION
CAISSON SHIPPING CONTAINER
GUIDE RAILS
LOADING AND STATIC TEST FACILITY (WET CONDITION)
LOADING AND STATIC (TEST FACILITY) DRY CONDITION

Figure 38

LARGE SOLID BOOSTER ROCKET

INSULATION DESIGN FOR 260-IN.-DIA MOTOR

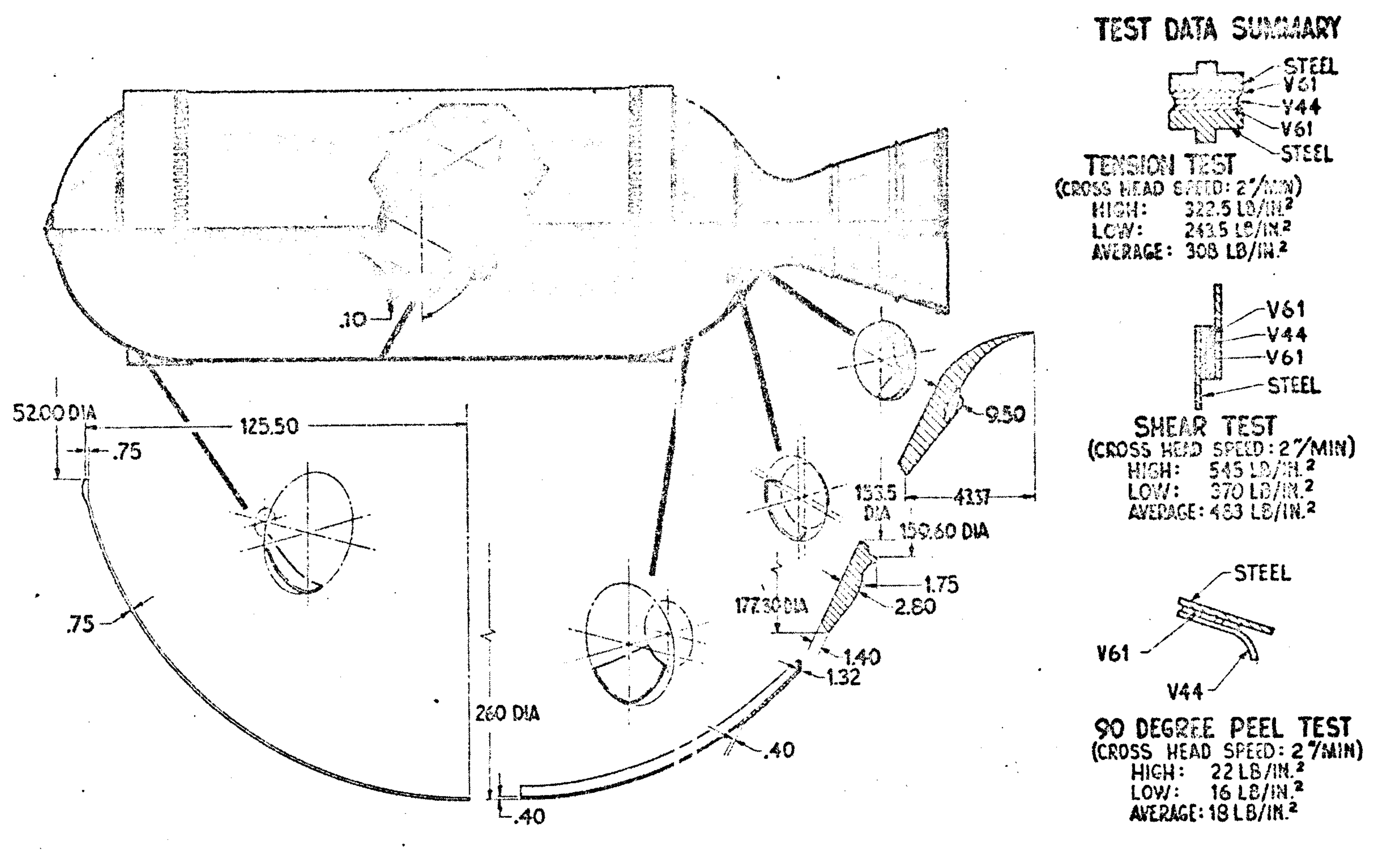


Figure 39

INSULATION

- NEW MASTIC FORMULATION DEVELOPED
  - CHEAPER THAN PRE-MOLDED OR SHEET MATERIAL
  - EASIER TO INSTALL
  - EQUAL OR SUPERIOR PERFORMANCE
- PROCESSING
  - CURRENT BATCH SIZE (35 LB), MIX TIME (20 MIN), POT LIFE (2 HR AT 100F) AND MIXERS FULLY ADEQUATE FOR PROCESSING INSULATION FOR FULL SCALE MOTORS
- INSTALLATION - TWO MAN CREW
  - BY HAND TROWELLING AND PNEUMATIC TAMPING - 70 LB/HR - LARGE GROWTH POTENTIAL
- TESTS INCLUDE
  - 6-TX-24 MOTORS (125 LB. MATERIAL EVALUATION MOTOR)
  - 2-100-INCH DIAMETER CHAR MOTORS (1-COMPLETE; 1 READY FOR TEST)
  - 2-65-INCH DIAMETER TU-418.01 SUB-SCALE MOTORS (1-COMPLETE; 1 READY FOR TEST)
- PERFORMANCE IN 65-INCH MOTOR

	HEAD END	FAR AFT END	CYL SECTION
AVG THICKNESS BEFORE TEST	0.666 IN.	3.032 IN.	N/A
AVG THICKNESS AFTER TEST	0.612 IN.	2.803 IN.	N/A
DESIGN EROSION RATE	4.0 MILS/SEC	5.9 MILS/SEC	NONE
ACTUAL EROSION RATE	1.58 MILS/SEC	4.34 MILS/SEC	NONE

Figure 40

BURNING AREA INCREASE AND MAXIMUM P_c WITH VARIOUS FAILURES

	Failure Category	% Area Increase At Time of Maximum P_c	Maximum P_c
1.	Full-Length, Full-Web Depth Grain Crack	17%	837
2.	Full Forward Boot Bond Separation	3.3%	720
3.	30-in.-long Cylindrical Bond Separation	2.7%	688
4.	100-in.-long Cylindrical Bond Separation	9%	750
5.	222-in.-long Cylindrical Bond Separation	20%	870

Minimum Chamber Failure Pressure = 870 psi

Figure 42

SENSOR CONCEPTS: INTEGRAL LINER (PHASE II)

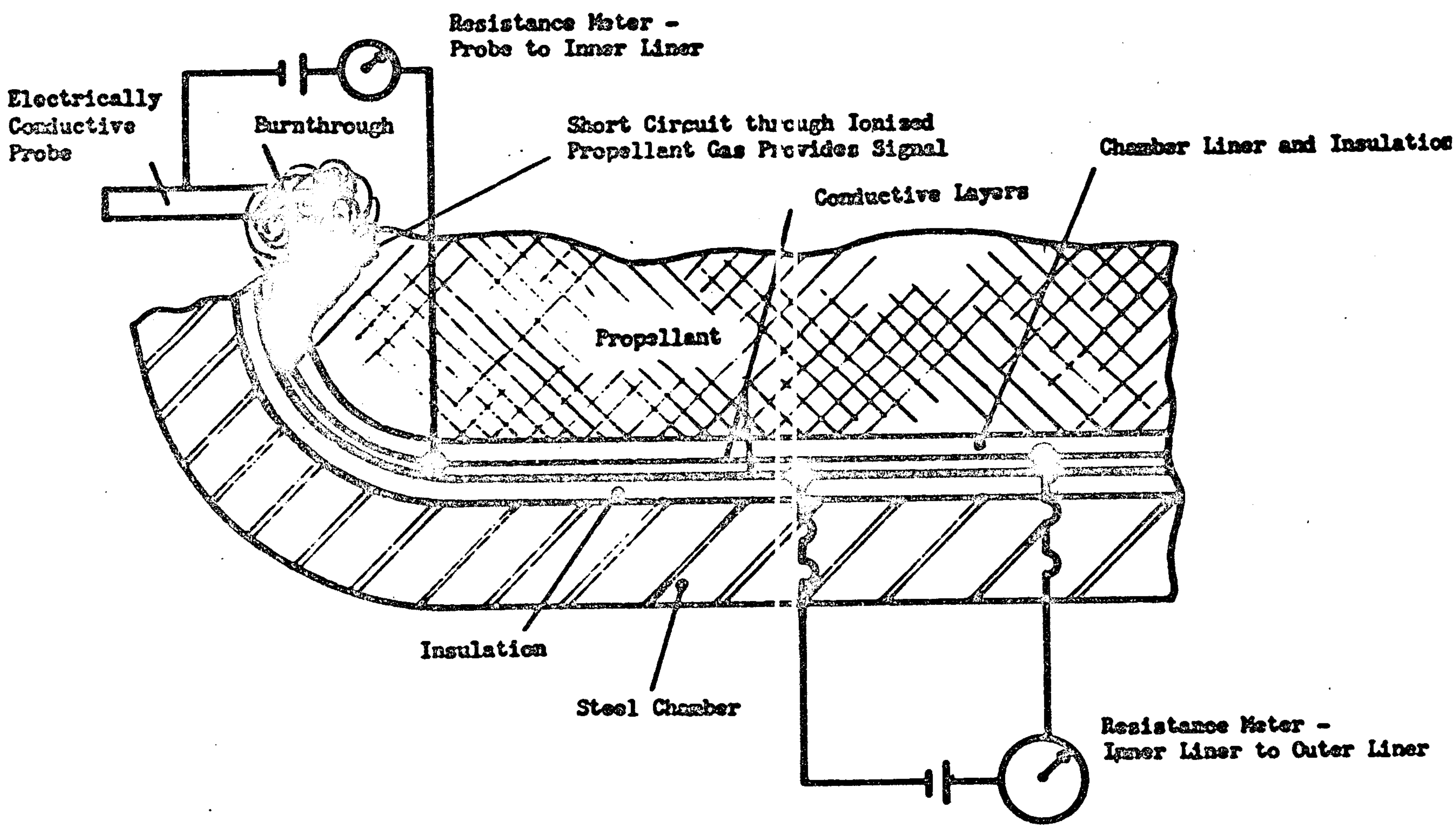


Figure 43

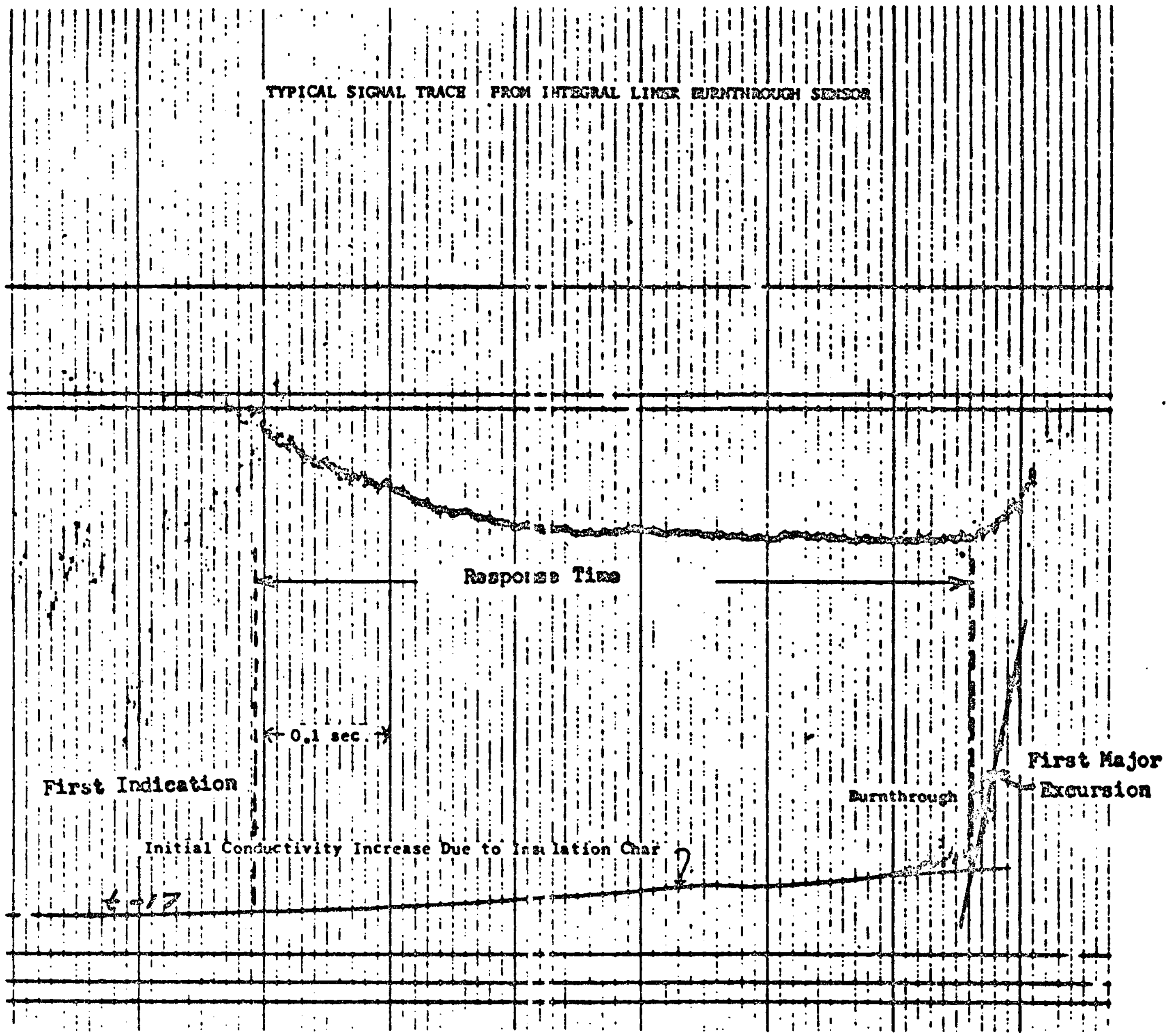
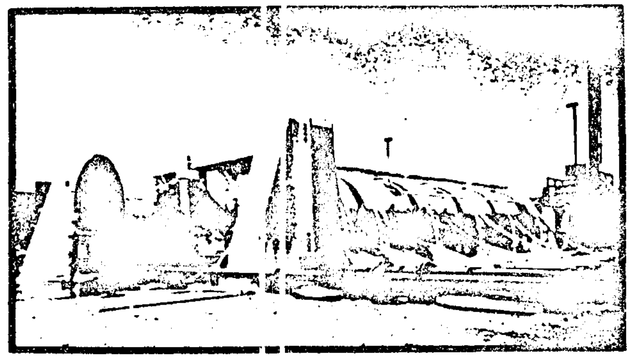

TYPICAL SIGNAL TRACE FROM INTEGRAL LINER BURNTHROUGH SENSOR
Response Time
0.1 sec.
First Indication
Initial Conductivity Increase Due to Insulation Char
Burnthrough
First Major Excursion

Figure 44

LARGE SOLID BOOSTER ROCKET

ACTUAL COST FOR 120 KS-600,000 MOTOR



COMPONENT	COST
CASE	$ 316,000
INSULATION	60,000
CLOSURE-NOZZLE	83,000
EXIT CONE	73,000
IGNITER	5,000
SUB TOTAL	**$537,000**
PROPELLANT	433,000
TOTAL COST FOR MOTOR LESS TVC	**$970,000**

TOTAL COST PER LB-$2.75

Figure 46

260-IN.-DIA MOTOR PRODUCTION COSTS

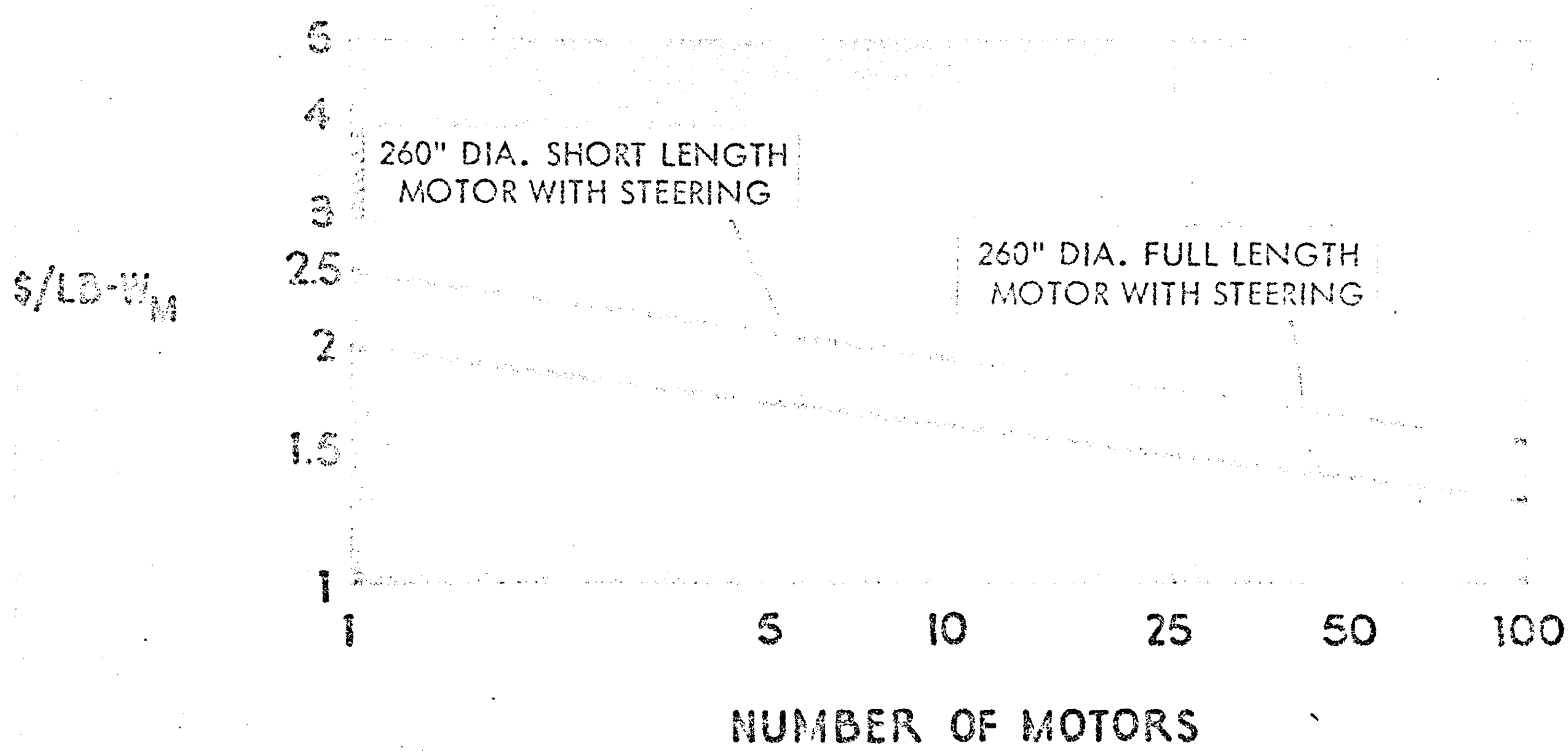


Figure 17

GPO 878-075